AN AUTOMATIC STARTUP SYSTEM FOR THE LIVERMORE WATERBOILER NUCLEAR REACTOR

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UNITED STATES
NAVAL POSTGRADUATE SCHOOL

THESIS

AN AUTOMATIC STARTUP
SYSTEM FOR THE LIVERMORE
WATERBOILER NUCLEAR REACTOR

BY

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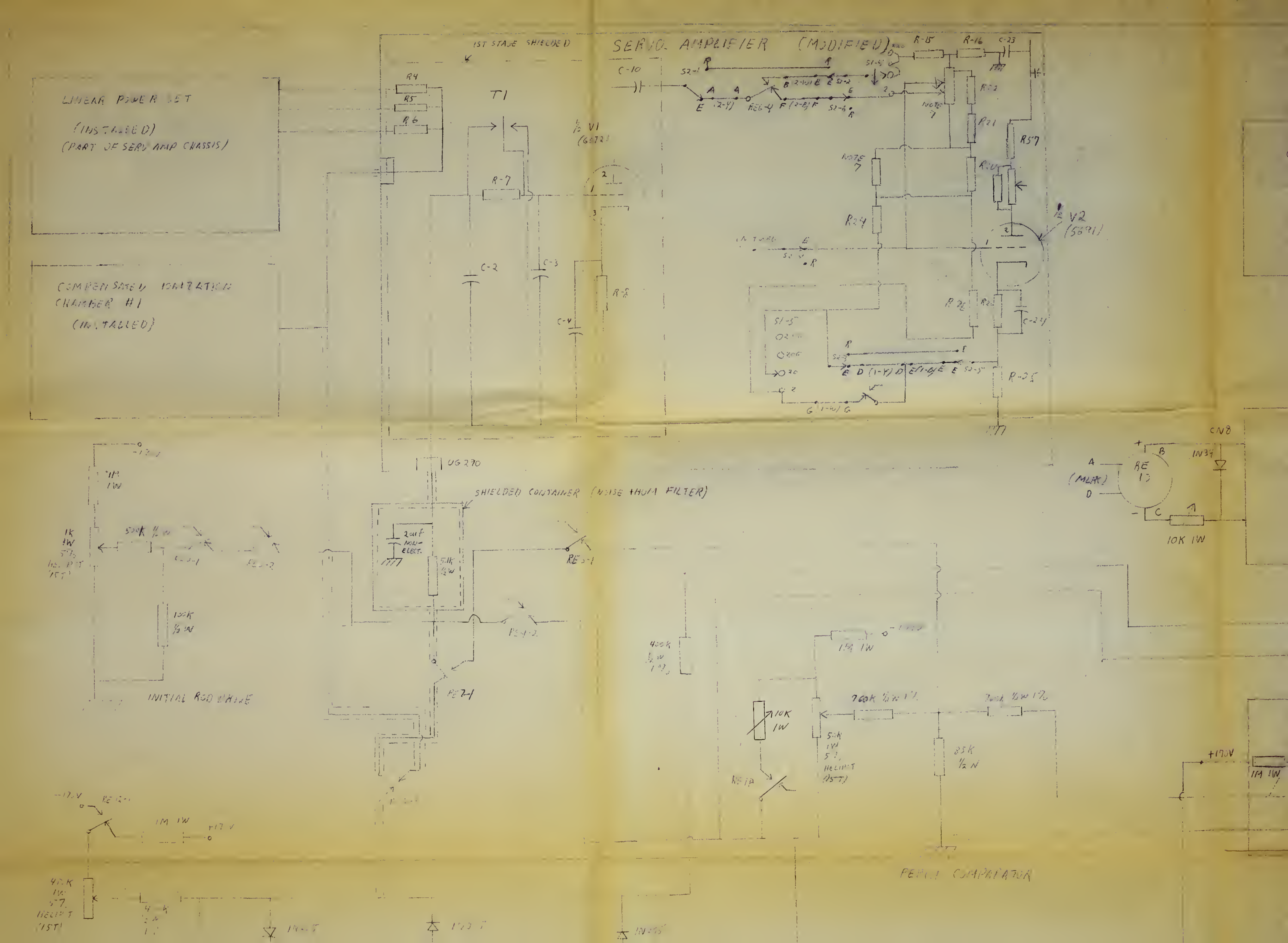
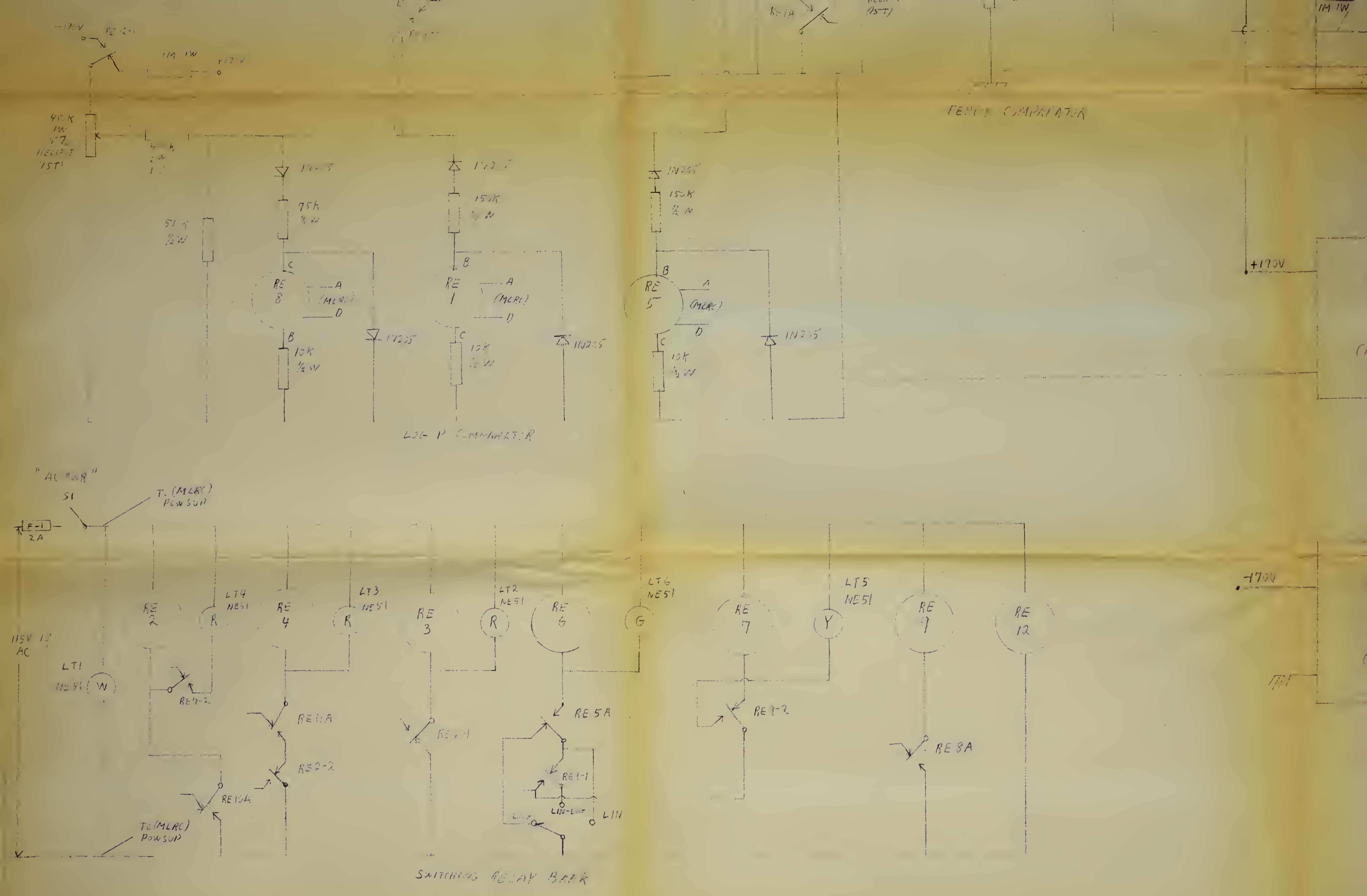
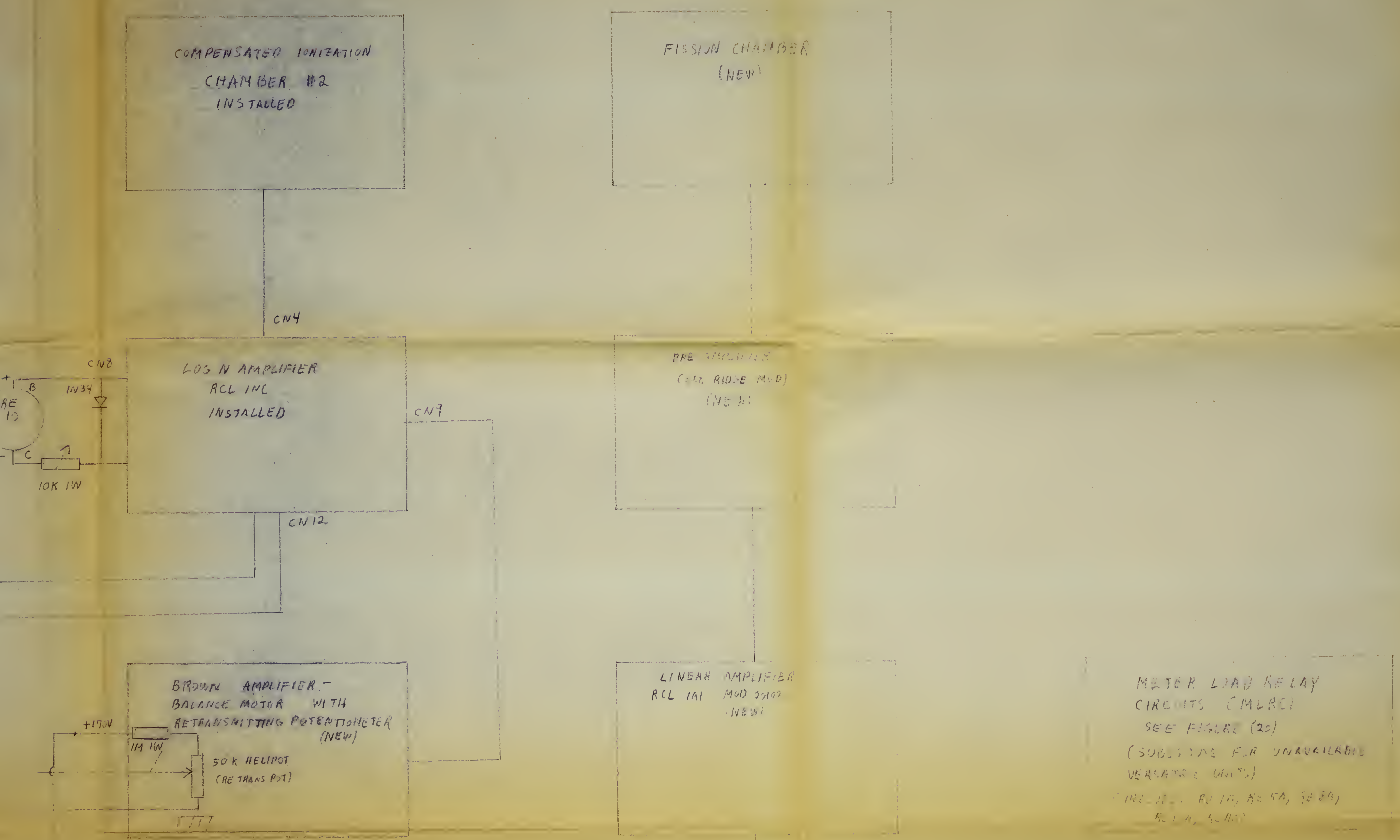


SERVO AMPLIFIER (MODIFIED)
1ST STAGE SHIELDED
LINEAR POWER SET
(INSTALLED)
(PART OF SERV AMP CHASSIS)
COMPENSATED IONIZATION
CHAMBER #1
(INSTALLED)
T1
R4
R5
R6
R-7
C-2
C-3
C-4
C-10
R-15
R-16
C-23
R21
R57
R24
R-25
NOTE 7
½ V1
½ V2
(5691)
UG 290
SHIELDED CONTAINER (NOISE +HUM FILTER)
CN8
IN34
RE 13
10K 1W
10K
1W
+170V
1M 1W
INITIAL ROD WAVE

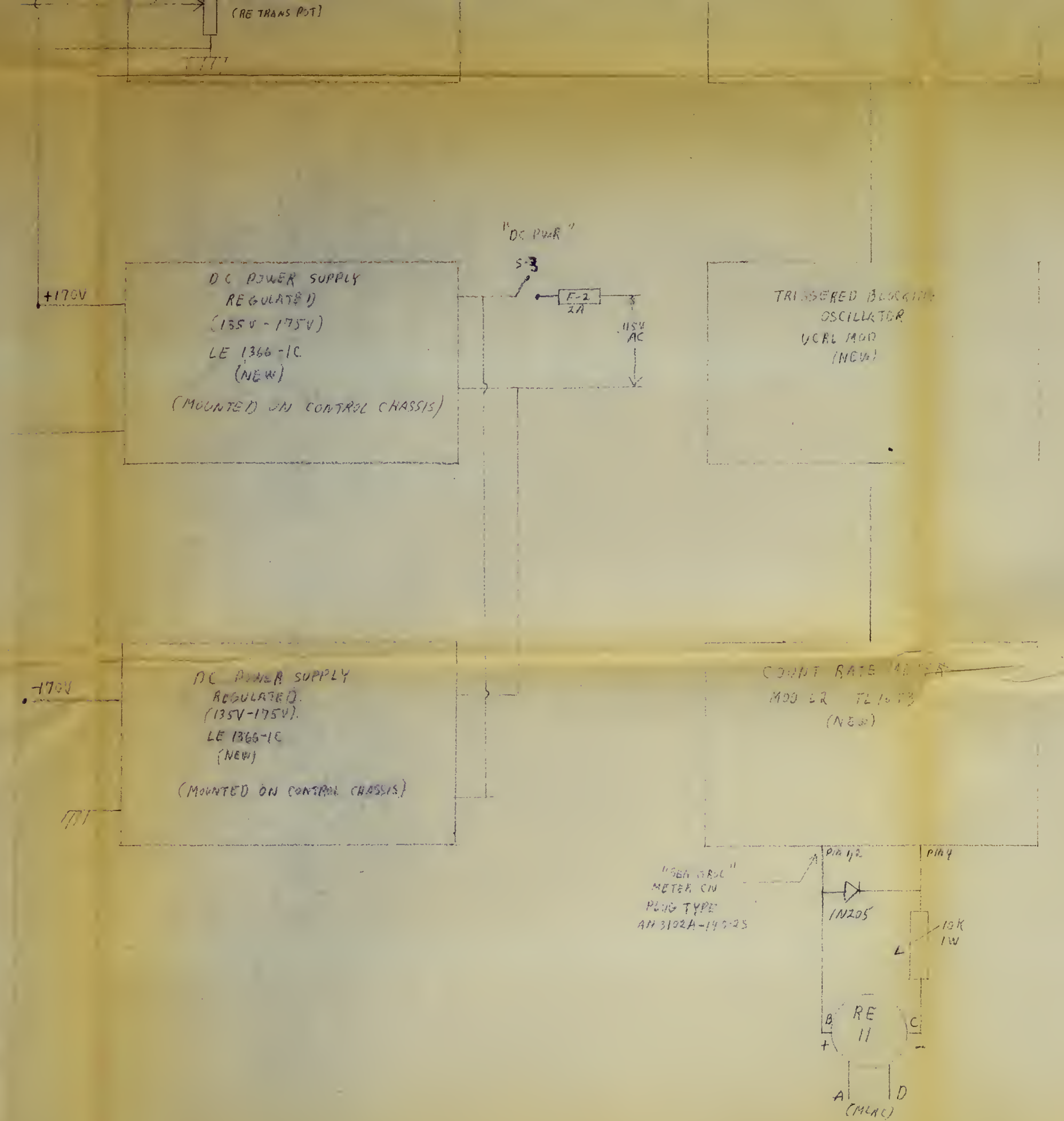


75K
15K
½W
RE 8
RE 1
RE 5
(MLRC)
+170V
LOG P COMPARATOR
"AC PWR"
S1
T. (MLRC) POW SUP
2A
115V AC
LT1
LT4 NE51
LT3 NE51
LT2 NE51
LT6 NE51
LT5 NE51
RE 2
RE 4
RE 3
RE 6
RE 7
RE 12
RE 5A
RE 8A
LIN
TC (MLRC) POW SUP
SWITCHING RELAY BANK



COMPENSATED IONIZATION
CHAMBER #2
INSTALLED
FISSION CHAMBER
(NEW)
CN4
CN8
LOG N AMPLIFIER
RCL INC
INSTALLED
1N34
10K 1W
CN9
CN12
PRE
RIDGE
BROWN AMPLIFIER -
BALANCE MOTOR WITH
RETRANSMITTING POTENTIOMETER
(NEW)
+170V
1M 1W
50 K HELIPOT
(RE TRANS POT)
LINEAR AMPLIFIER
RCL INC
(NEW)
METER LOAD RELAY
CIRCUITS (MLRC)
SEE FIGURE (20)

VERSATROL UNITS)
(INC ... RE 10, RE 5A, RE 8A)



NOTES

1. RELAYS 1, 5, 8, 10, 11 ARE METER RELAYS FOR USE WITH VERSATROL CONTROL UNITS FOR LOAD RELAY CIRCUITS
2. RELAYS 2, 3, 4, 7, 9, 12 ARE DPDT
   { TYPE DOSX7T (OHMITE) OR
   { BO 5A 115 (ALLIED)
3. RELAY 6 IS 4PDT TYPE DOX 55T (OHMITE)
4. ALL RELAYS ARE SHOWN IN DEENERGISED POSITION
5. R, C, AND V NUMBERS SHOWN IN SERV AMP BLOCK AGREE WITH THOSE SHOWN ON UCRL PRINT TL 23745
6. FOR BEST OPERATION OF LINEAR POWER SET AT LOW LEVELS BOTH CONTROL CHASSIS AND LOGN AMPLIFIER SHOULD BE ISOLATED FROM CONSOLE GROUND
7. PART OF MOD A TAPPED BECKMAN POTENTIOMETER
8. IN SERV AMP SYMBOLS SUCH AS (1-Y) REFER TO YELLOW WIRE OF CABLE 1 FROM SERV AMP TO CONTROL CHASSIS.
9. E ENERGISE, R RESTORE POSITIONS OF SWITCH S2 ON BASE OF SERV AMP CHASSIS. FOR USE OF AUTO CONTROL SYSTEM SWITCH S2 SHOULD BE IN "E" POSITION
10. FOR IDENTIFICATION OF CN NUMBERS ON LOGN AMPLIFIER AND CONNECTOR TYPES REFER. ACL DWG 20103-1 "LOGN AMPLIFIER".

WATER BOILER AUTOMATIC CONTROL SYSTEM FIGURE 18

DRAWN BY SCHRADER

NP - 8550

AN AUTOMATIC STARTUP SYSTEM FOR THE LIVERMORE WATERBOILER NUCLEAR REACTOR

* * * * * * * * *

Joseph L. Randolph

AN AUTOMATIC STARTUP SYSTEM FOR THE LIVERMORE WATERBOILER NUCLEAR REACTOR

by

Joseph L. Randolph

Lieutenant, United States Navy

Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN
ENGINEERING ELECTRONICS

United States Naval Postgraduate School
Monterey, California

1 9 5 9

AN AUTOMATIC STARTUP SYSTEM FOR THE LIVERMORE WATERBOILER NUCLEAR REACTOR

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This work is accepted as fulfilling the thesis requirements for the degree of

MASTER OF SCIENCE

IN

ENGINEERING ELECTRONICS

FROM THE

UNITED STATES NAVAL POSTGRADUATE SCHOOL

ABSTRACT

Design calculations and experimental test results for an automatic startup system for the Livermore Waterboiler are presented. Automatic startup from near source level (below the period meter range) to full power (500 watts) has been demonstrated with this system. Multidecade logarithmic power control also was demonstrated in the range 0.05 watts to 500 watts. Demanded period is continuously variable in the range ∞ to 10 seconds. Demanded power level is continuously variable from 0.05 watts to 500 watts. Photographs of the control chassis and a schematic diagram of the control system are included.

The Livermore Water Boiler Power Transfer Function was measured in the frequency range 0.1 rad/sec to 157. rad/sec by the pile oscillator technique. Calculations and results of the measurement are included.

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ACKNOWLEDGEMENT

The work discussed in this paper was done at the Lawrence Radiation Laboratory, Livermore, California, under the able guidance of Dr. James Carothers, Dr. Robert E. Finnigan and Mr. Frederick Shon, without whose help the project could not have been accomplished. Mr. Stanley Ross provided analog computer support. Messrs. Frederick Shon, Ernest Hill and William Wade designed the pile oscillator. The LPTR operating crew and electronics staff, the Controls Group of R Division, and EE department personnel contributed valuable suggestions, assisted in performing experiments and provided necessary equipment.

Professors David B. Hoisington and Robert D. Strum of the U. S. Naval Postgraduate School also contributed generously of their time and experience.

To all who have so generously assisted in this project, the author is sincerely grateful.

INTRODUCTION

There exist today in several countries of the world devices which control nuclear reactors automatically over several decades (1, 2, 3). Nevertheless, there are many unsolved problems of automatic reactor control. Some of these problems exist because present day nuclear reactors have been readily controllable by human operators and, therefore, the demand for automatic control has not been acute. Furthermore, in its own right, the novelty of the

controlled element is an important factor in the state of development of automatic control.

What does automatic control of the reactor over several decades of power level have to offer? In answering this question, one must consider the type of reactor for which automatic multidecade control is proposed.

In a research reactor, automatic multidecade control is an additional safety feature because it frees the operator from certain specific tasks, thereby enabling him to observe more readily the overall behavior of the reactor during a change in power level. In routine irradiation of materials, automatic multidecade control provides a means of accurately programming the flux levels and rate of change of flux levels desired.

In certain new power reactors, automatic multidecade control becomes a necessity for proper operation of the reactor because of Xenon poisoning effects, or requirements on rate of change of power demand, or because of the complexity of instrumentation.

The regions in which little unclassified work has been done include automatic startup of a reactor from near source level where reactor period information is not available, and multidecade Log Power Control.

In an attempt to demonstrate the feasibility of these control modes, and to evaluate certain aspects of design philosophy embodied in Tory II (4) as well as to provide an

automatic startup feature for the Livermore L-3 Waterboiler, a ten week program to design and test a reactor control device was undertaken.

Symbols used throughout this paper are defined in Appendix I.

DESIGN REQUIREMENTS AND PHILOSOPHY.

A. The automatic control system for the Livermore Water Boiler was designed to include the following features:

1. Automatic startup of the Water Boiler was to be from low power to demanded power.

2. Demanded period was to be continuously variable in the range ∞ to 10 seconds.

3. Demanded final power level was to be continuously variable in the range 0.01 watts to 500 watts.

B. Aspects of the design philosophy embodied in a proposed automatic control system for the Tory II Reactor (4) to be demonstrated included:

1. Multidecade period control.

2. Multidecade log power control

3. Control Mode Switching.

C. Automatic Startup from near source level, where period information is not available for control purposes was to be demonstrated.

In attempting to complete the design a unified or "systems engineering" approach was stressed.

The design philosophy was centered about flexibility. This was dictated by the varied design requirements. Of

course, implicit in any desi n requirements for nuclear reactor control systems is the consideration of safety. A third consideration was economy and maximum utilization of previously installed control equipment.

Other desirable features included: reliability and simplicity of construction, of maintenance, and of operation.

In keeping with the aims of flexibility and maximum utilization of previously installed equipment, it seemed logical that the control device should imitate the human operator in so far as possible, consistent with the other design requirements.

DESIGN PROCEDURE.

It was first necessary to obtain a detailed knowledge of the water boiler reactor, its existing controls, its kinetic behaviors, both theoretical and actual. This included a theoretical study of nuclear physics, nuclear reactors in general, the water boiler in particular, as well as a review of the instruction books for the associated equipments. In addition, it was necessary to observe several manual startups in order to learn the procedure used by the operators and the actual behavior of the reactor.

In order to know the actual behavior of the existing control elements it was necessary to make transfer function measurements in some cases. This information was of value in the design process of control loop synthesis and stability investigations

Accordingly, after a preliminary study, it was decided

to perform as many as possible of the following experiments, under various conditions of loading where necessary.

1. Log N Amplifier Transfer Function Measurement from Input to:

    a. Period Output connector

    b. External Power Meter connector

    c. External Period Meter connector

2. L-3 Reactor Transfer Function by one or more of the following methods:

    a. Pile Oscillator Frequency Response (5)

    b. Use of Autocorrelator with steady state measurements (6)

    c. Direct application of a Unit Impulse of Reactivity and computation of Fourier Transform of response.

    d. Direct application of a Step in Reactivity with differentiation of response and computation of Fourier Transform of result.

After a sufficient knowledge of the existing controls had been obtained, additional control elements were designed as necessary, and control loops were designed in accordance with the design purpose and philosophy.

These control loops were then analyzed for stability space and speed of response using linear analysis techniques.

This was followed by an analog computer study of the entire control system including multimode startup and switching with non-linearities included in the simulation.

Preliminary construction and testing of control subunits proceeded concurrently with control loop design. The next step was construction and debugging of the control chassis, including an operational test of the control chassis with the analog computer.

Upon completion of these tests, the control system was installed at the reactor and used to operate the reactor. Several tests were run, the system was modified as necessary to improve performance. A system evaluation was made and recommendations for an improved finalized version of the control system were formulated.

DESCRIPTION OF THE REACTOR AND EXISTING CONTROLS

The Livermore L-3 Water Boiler is a 500-watt solution type reactor. The core is a 12-1/2 in. O. D. stainless steel sphere of uranyl sulfate solution (UO_2SO_4). A graphite reflector is used. Light water is the moderator.

The reactor is a research type, the maximum neutron flux available is $2X10^{10}$ neutrons/cm^2 -sec at the glory hole through the center of the sphere. Figure 1 is a schematic representation of the reactor.

To remove the fission heat from the core, distilled water is circulated in tubing through the core and through a heat exchanger employing a Freon condensing system.

A closed gas handling system is used to circulate a carrier gas over the fuel solution for removal of volatile fission products, hydrogen, oxygen and water vapor. The hydrogen and oxygen are catalytically recombined, and all water vapor is condensed and returned to the core

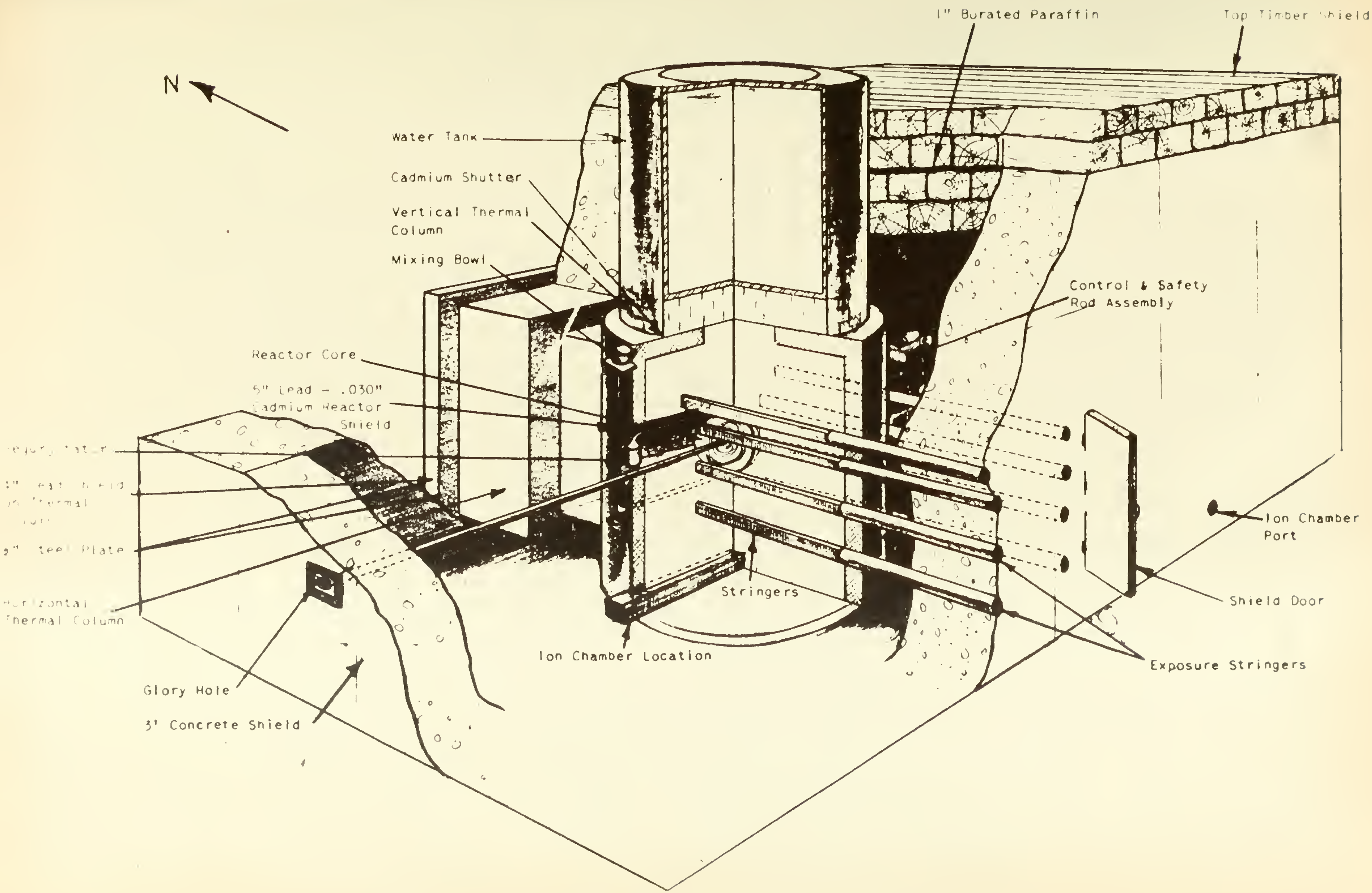


FIG. I - REACTOR INSTALLATION - ISOMETRIC VIEW

(COURTESY LAWRENCE RADIATION LAB)

tank. There is provision in the gas handling system for storage of volatile fission products and periodic removal of radioactive gases. Pressure in the gas system is maintained below atmospheric to prevent escape of radioactive gasses if a leak should develop.

The control and safety rod system includes two safety rods, a coarse control rod, and one regulating rod.

The two safety rods are withdrawn by electric motor drive systems. The motors move carriages by means of a chain drive. The carriages carry electromagnets which when energized will allow withdrawal of the safety rods. The motors are Boston Ratio motors (57.5RPM). The safety rods may be withdrawn sequentially at a rate of about 8 seconds per rod. The rods are stainless steel tubes packed with boron carbide. Safety #1 controls 1.40% ΔK, #2 controls 1.20% ΔK; together they control about 2.50% ΔK.

The coarse control rod controls approximately 1.40% in reactivity, the regulating rod about 0.67%. Together they control about 2.00% ΔK.

The coarse control rod is moved manually at two speeds (0.5 cm/sec and 0.05 cm/sec). The electric drove system is a 1/15 hp Bodine speed reducer motor. There is one fast motor and one slow motor. A magnetic clutch is used with a rack and pinion gear to move the coarse rod.

The regulating (fine control) rod is equipped with a linear power set servo system. This is shown in block diagram form in Figure 2.

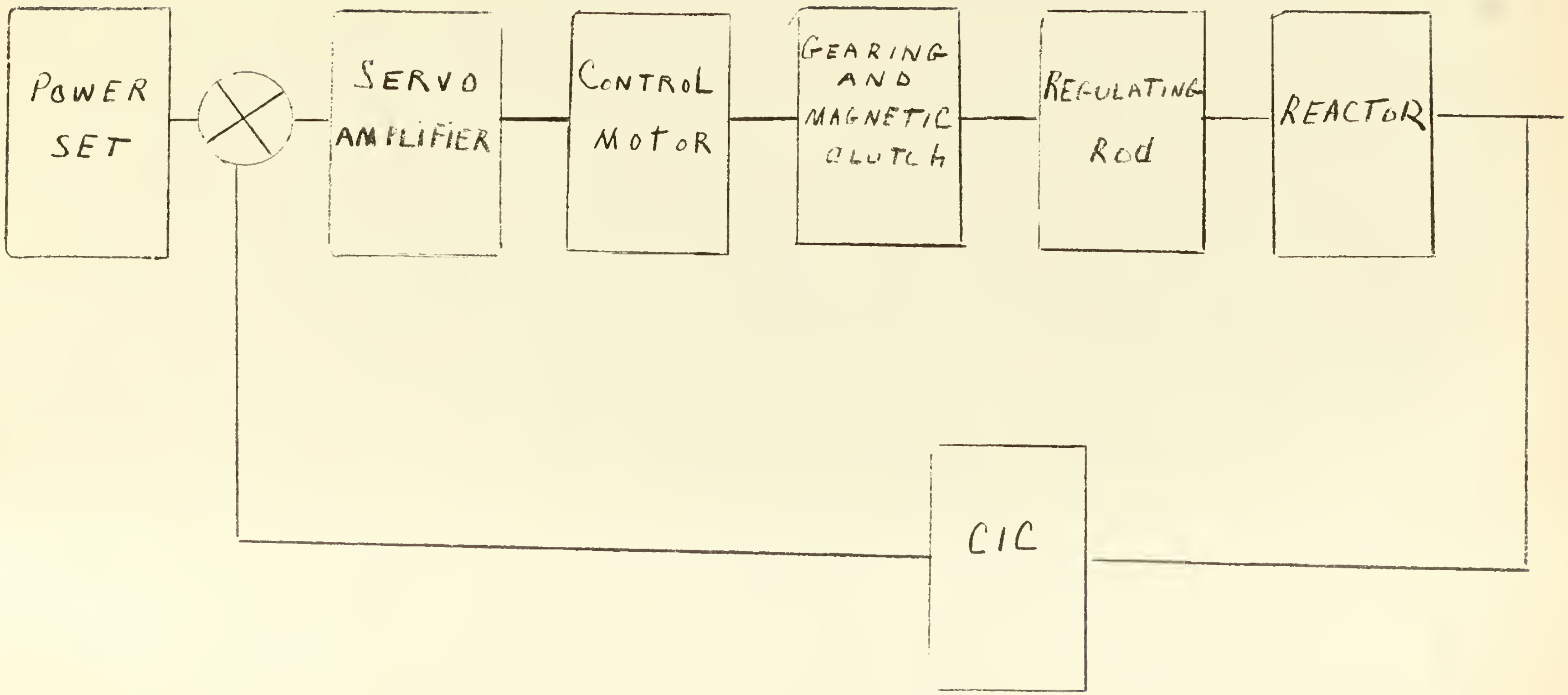

POWER SET
SERVO AMPLIFIER
CONTROL MOTOR
GEARING AND MAGNETIC CLUTCH
REGULATING ROD
REACTOR
CIC

FIGURE 2

This system and its component parts will be examined in detail in this paper.

In addition to the gas and cooling system indicators and control units, there are various power level indicating channels installed.

For low level start-up there are two Berkeley Count Rate Meters (CRM) using BF3 detectors.

For the upper six decades of operation, two Berkeley micro-microammeters using compensated ionization chambers as detectors are installed. In addition there is a Log-N Amplifier which furnishes Log Power and Period Information. This Amplifier also uses a gamma compensated ionization chamber (CIC) as a detector. For the purpose of obtaining watt-hrs. information, a Berkeley CRM - Scaler - Fission Chamber Channel is used. Brown Recorders are used to give a record of operation. Any of the above listed power indicating instruments will scram the reactor on excessive power level.

The following is a list of scram actuators:

1. Excessive power level
2. Fast period
3. Excessive sweep-gas pressure
4. Excessive fuel temperature
5. Excessive hydrogen concentration in sweep gas
6. Earthquake
7. Low gas flow rate
8. Water leak in gas -- pressure regulating system
9. Operator Action

10. Instrument power lost

11. Startup source not in place

12. Biological Shield Doors open

13. Safety Switches open inside biological shield

For a more complete but summary discussion of the reactor, its characteristics and controls, Ref. 7 from which this summary is for the most part taken, should be consulted. For a detailed discussion, references 8, 9, 10, 11, 12, 13, and 14 should be consulted.

ANALYSIS OF SONE CONTROL LOOP ELEMENTS
(All symbols are defined in the Appendix 1)

A. SERVO AMPLIFIER

The equations and constants shown below are based upon consideration of the actual amplifier circuit shown in Ref.16.

Note that the amplifier gain is defined from considerations of a reactor transfer function based upon constants which are used in Ref 15, but not in this paper. More recent constants are available and are used in the computer study of the system. Moreover, in the linear analysis to follow an asymptotic form of the reactor transfer function is used.

Nevertheless, because the amplifier has been built based upon the design calculations in Ref 15 and with K_A' changing as shown in Ref 15, then K_A will be as defined in Ref. 15 and indicated below.

Transfer Function: $$KG = \frac{K_A}{1+T_A S} = \frac{K_A}{(1+\frac{1}{60}S)} \qquad (1)$$

$$K_A = \frac{K_S}{K_I\, K_A'\, K_M\, K_C} \qquad (2)$$

where $$K_S = \frac{0.09}{n_o} = \frac{0.09}{n_{o1}P_o} \tag{3}$$

$K_C = 0.5\text{X}10^{-4}$ to $2\text{X}10^{-4}$ reactivity/cm

(in linear region choose $K_C = 0.0192\% \Delta K/\text{cm}$)

$$K_A' = \begin{cases} \frac{\sqrt{2}}{\pi}\text{X}1.6\text{X}10^{5} & \text{for } P_o = (2000 - 200) \text{ watts} \\ \frac{\sqrt{2}}{\pi}\text{X}1.6\text{X}10^{6} & \text{for } P_o = (200 - 20) \text{ watts} \\ \frac{\sqrt{2}}{\pi}\text{X}1.6\text{X}10^{7} & \text{for } P_o = (20 - 1) \text{ watts} \end{cases} \tag{4}$$

$$K_I = 5\text{X}10^{-8} \frac{\text{amp}}{\text{watt reactor power}} = \frac{5\text{X}10^{-8}}{n_{o1}}$$

$K_M = 2.5\text{X}10^{-3}$ cm/sec/volt

<u>P_o = 1W</u>;

$$K_A = \frac{9\text{X}10^{-2}\text{X}\, n_{o1}}{n_{o1}\,\text{X}5\text{X}10^{-8}\,\text{X}\,\frac{\sqrt{2}}{\pi}\text{X}1.6\text{X}10^{7}\text{X}2.5\text{X}10^{-3}\text{X}1.92\text{X}10^{-4}} = 0.518\text{X}10^{6} \tag{5}$$

<u>P_o = 10W</u>;

$$K_A = \frac{9\text{X}10^{-2}\,\text{X}n_{o1}}{10n_{o1}\,\text{X}5\text{X}10^{-8}\,\text{X}\,\frac{\sqrt{2}}{\pi}\,\text{X}1.6\text{X}10^{7}\,\text{X}2.5\text{X}10^{-3}\text{X}1.92\text{X}10^{-4}} \tag{6}$$

$K_A = 0.518\text{X}10^{5}$

<u>P_o = 100W</u>;

$$K_A = \frac{9\text{X}10^{-2}\text{X}\, n_{o1}}{100n_{o1}\,\text{X}5\text{X}10^{-8}\,\text{X}\,\frac{\sqrt{2}}{\pi}\,\text{X}1.6\text{X}10^{-6}\text{X}2.5\text{X}10^{-3}\text{X}1.92\text{X}10^{-4}} \tag{7}$$

$K_A = 0.518\text{X}10^{5}$

$P_o = 500W$;

$$K_A = \frac{9X10^{-2} X\ n_{o1}}{500n_{o1}\ X510^{-8}\ X\ \frac{\sqrt{2}}{\pi}\ X1.6X10^{5} X2.5X10^{-3}\ X1.92X10^{-4}} \quad (8)$$

$$K_A = 0.1036X10^6$$

TABLE 1

P_o	K_A	K_A'
1W	$0.518X10^6$	$7.2X10^6$
10W	$0.518X10^5$	$7.2X10^6$
100W	$0.518X10^5$	$7.2X10^5$
500W	$0.1036X10^6$	$7.2X10^4$

The relationship holds that:

$$K_A K_{A'} = \frac{K_1}{P_o} \quad (9)$$

The maximum A-C gain available from the amplifier is $4X10^6$ for 100% coarse gain control setting.

If one desires to incorporate this amplifier in either Log P* or PER* control loop, one might use as a conservative gain available figure, that corresponding to 50% coarse gain control setting of $K_A = 2X10^6$. A fixed gain amplifier will be desirable in Log P and PER loops because the logarithmic characteristic provides compensation for increasing power level, as does the inverse period characteristic in an approximate manner.

* Appendix I

Additional servo amplifier notes:

The servo amplifier power supply furnishes, in addition to the polarizing voltages, two phases of a three phase supply. One phase is used for filament voltage (phase B) and the second phase is used to drive the synchronous converter. A phase sensitive detector (galvanometer) is supplied for determining the phase of the output voltage as leading or lagging phase A.

When in manual operation, the output of the servo amplifier is dumped into a dummy load external to the amplifier. In automatic operation the amplifier output is applied to the control winding of the Control Motor.

One should point out that the amplifier as designed is adequate for its designed function of linear power set control. However, if one is to use this amplifier in other control loops additional problems arise and modifications become necessary.

It was noted experimentally that the amplifier overloads gracefully only up to a certain point. Beyond this point, wave form distortion occurs and the output signal is in error. It is important from a design standpoint to avoid operation in this region of distortion. However, it is necessary to operate the amplifier normally at saturation because of the high gain.

The peak output voltage of the amplifier is 200 volts. The gain nominally may be as high as $2X10^6$ which means a saturation input signal to the converter is of the order of

$$\frac{200 \text{ volts}}{2X10^6} = 0.1 \text{ millivolt}$$

Thus, if possible, any modifications to the imput stage of this amplifier should be avoided because of the inherent noise problems. However, an examination of the new Log P control loop indicates a need for all of this $2X10^6$ gain.

Furthermore, because the amplifier as designed is a variable gain device, modifications will be necessary to provide fixed gain or at least nearly fixed gain for use in Log P and P&R control loops.

In addition there is the requirement of providing for restoration to manual startup conditions in keeping with the design criterion of flexibility.

B- SERVO CONTROL MOTOR AND GEARING

The control motor installed is a Transicoil type 2200 specification number 11. It is a two phase induction motor. The reference phase is phase A of a 208 volt supply. In manual operation phase BC or CB is applied to the control winding. In automatic operation phase A is shifted 90 degrees through the synchronous converter - amplifier circuitry and applied to the control winding of the motor, the resultant direction of shaft rotation depending on the phase of the voltage on the control winding with respect to the voltage on the reference winding.

The control motor drives the regulating rod through a 300:1 gear reduction and a rack and pinion arrangement.

Speed torque curves for the motor are given in Ref. 15.

A maximum RPM of 1600 corresponds to the maximum rod rate of 0.5 cm/sec.

The transfer function (as given by Ref 15) for control motor and gearing:

$$KG = \frac{K_M}{(1+T_m S)} \qquad (10)$$

where K_M = cm/sec/volt $= \frac{\text{max rod rate}}{\text{max voltage}}$ $\frac{0.5}{200}$ $2.5\text{X}10^{-3}$ (11)

and $T_M = 1/50$ sec

$$KG = \frac{25\text{X}10^{-3}}{(1+[1/50]S))} \qquad (12)$$

C-REGULATING ROD (FINE CONTROL ROD)

The regulating rod contains about one pound of boron carbide in a stainless steel sleeve. Its total worth is about 0.57% reactivity, distributed roughly in cosinusoidal fashion over about 80 cm. of length. Maximum rod speed is 0.5 cm/sec.

Transfer function:

The transfer function is essentially frequency independent in the frequency range of interest and is assumed constant in the analysis to follow. This latter approximation is valid to the extent that in most circumstances the rod will be used so that its maximum region of worth is controlling the reactor. This maximum worth occurs where the rod worth is nearly linear with length.

The transfer function has been evaluated based upon

experimental data entitled <u>Fine</u> <u>Control</u> <u>Rod</u> <u>Traverse</u>, dated 4/13/54 (part of Ref 14). Reproduction of this curve is included as Figure 3.

In the linear region

$$K_{\Lambda} = \frac{\delta k}{\delta x} = \frac{(0.4-0.3)\%\ K}{(22.8-17.6)\text{cm.}} = \frac{0.1}{5.2} = \underline{0.0192\%\ K/\text{cm}} \tag{13}$$

or

$$K^{*} = \frac{K}{\beta_{eff}} = \frac{0.0192\%\ \Delta K/\text{cm}}{0.0855\%\ \Delta K/\$} = 2.25\text{X}10^{-2}\ \$/\text{cm} \tag{14}$$

D. L-3 NUCLEAR REACTOR

The Reactor Transfer Function (as given by Ref. 17) is:

$$\frac{\delta P}{\delta K} = \frac{P_o}{\beta_{eff}}\left[j\omega l^{*} + j\omega\sum_{i=1}^{5}\frac{a_i}{j\omega+\lambda_i} - \frac{\alpha^{*}KP_o}{j\omega+\gamma} - \frac{\phi^{*}GP_o}{j\omega+\sigma}\right]^{-1} \tag{15}$$

Figure 4 shows a possible block diagram representation of eqn (15).

For convenience of reference, the symbols used in equation 15 are listed below: (as they are defined in Ref. 16)

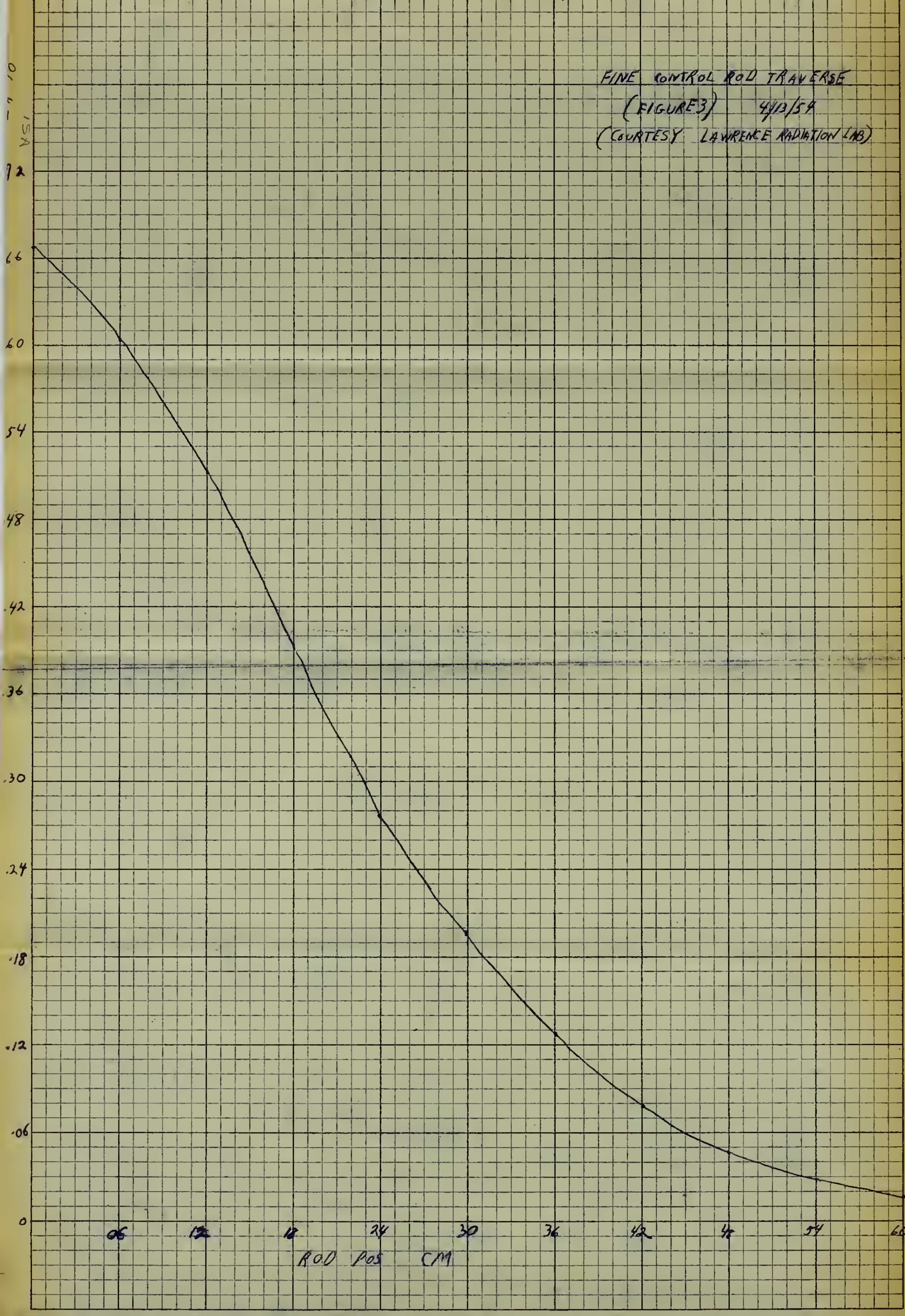
$\beta_{eff} = \gamma\beta$ = effective total fraction of all neutrons which are delayed.

$l^{*} = \frac{l}{\beta_{eff}} = 1.15\text{X}10^{-4}$ sec. This number was obtained experimentally by a measurement of the reactor transfer function. A detailed description of the measurement and results obtained comprises Appendix II

l = the "effective" neutron generation time in the reactor

l_o = neutron lifetime

a_i = the fraction of all delayed neutrons which belong to the ith delayed group,


FINE CONTROL ROD TRAVERSE
(FIGURE 3) 4/13/54
(COURTESY LAWRENCE RADIATION LAB)
72
.66
.60
.54
.48
.42
.36
.30
.24
.18
.12
.06
0
06
12
18
24
30
36
42
48
54
60
ROD POS CM

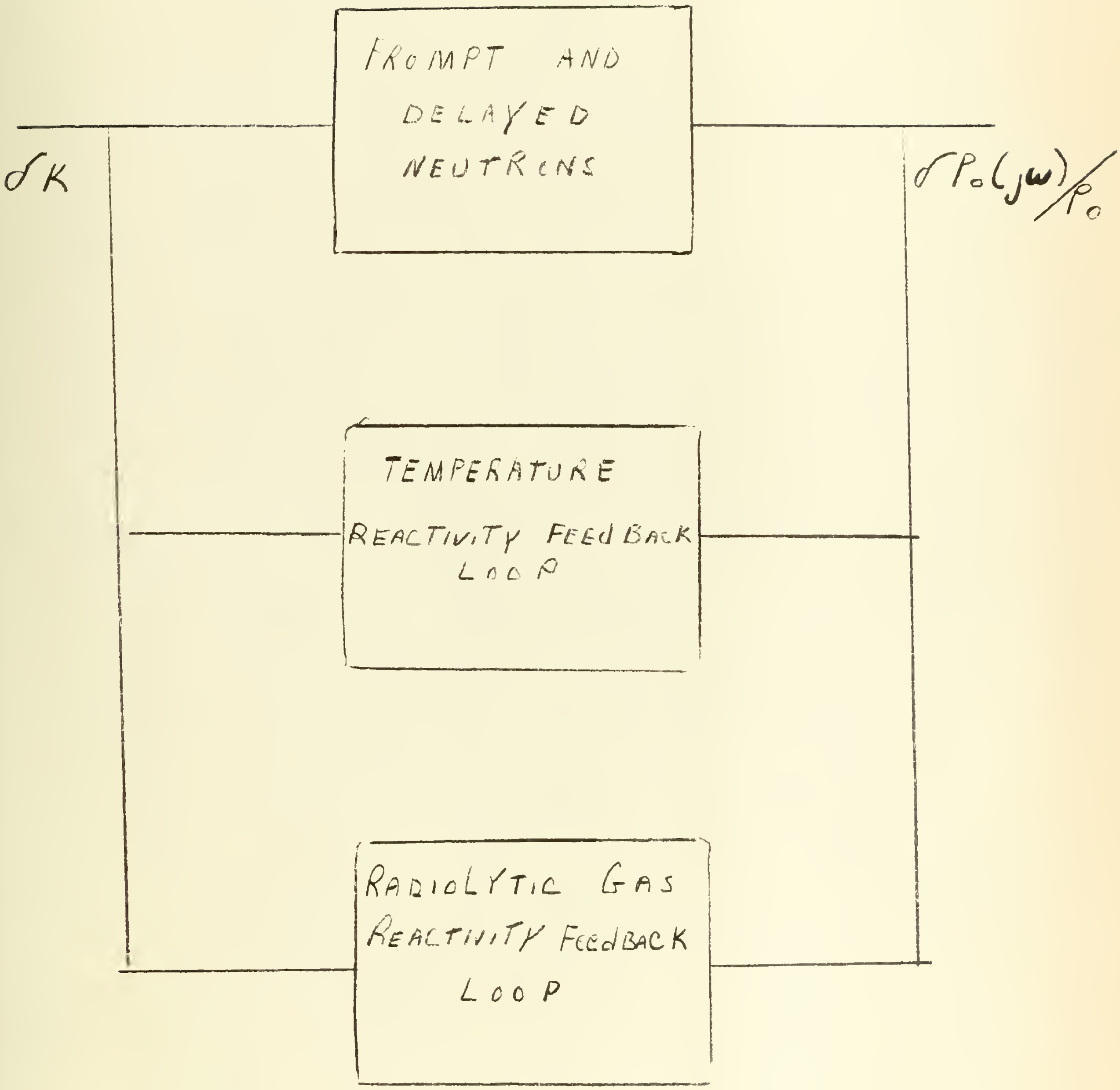

PROMPT AND
DELAYED
NEUTRONS
δK
δP₀(jω)/P₀
TEMPERATURE
REACTIVITY FEEDBACK
LOOP
RADIOLYTIC GAS
REACTIVITY FEEDBACK
LOOP

FIGURE 4

λ_i = ith neutron group decay constant

$\alpha^* = \alpha / \beta_{eff}$ = the temperature coefficient of reactivity in units of dollars

$\alpha = -2.6 \times 10^{-4}$ per degree centigrade

k = the adiabatic rate of increase of the space average temperature per unit total fission rate (or power) for the reactor.

k = 0.01428° C/KW-sec

the reciprocal of the characteristic mean time for loss of heat from the core, such that $\gamma T(t)$ is the rate of decrease of T (t)=($\frac{1}{100}$ sec^{-1}).

ϕ = the increase in reactivity of the reactor due to a unit increase in radiolytic gas volume (STP), that is, the void coefficient of reactivity in absolute units -7×10^{-6} cm^{-3} at STP

$\phi^* = \phi_{eff}$

G = the adiabatic rate of increase of the total volume at STP of radiolytic gas in solution per unit total fission rate (or power) for the reactor. G = 4.16 cm^3/Kw

G = 4.16 cm^3/Kw at STP

σ = the reciprocal of the characteristic time for loss of radiolytic gas from the core, such that V(t) gives the total rate of loss of gas from the soup.

σ = 0.5 sec^{-1} at STP

The Neutronic Data used are those given by Ref. 18

and is listed below for convenience of reference.

TABLE I

i	a_i/a	λ_i
1	0.038 ± 0.003	0.0127 ± 0.0002
2	0.213 ± 0.005	0.0317 ± 0.0008
3	0.188 ± 0.016	0.115 ± 0.003
4.	0.407 ± 0.007	0.311 ± 0.008
5	0.128 ± 0.008	1.40 ± 0.081

An asymptotic Form of L-3 Transfer function for the frequency range 0.01 to 1000 rad/sec may be considered.

The following equations were developed from a consideration of Figure 1 of Ref. 17 and are used in the loop stability analyses to follow.

In the frequency range of interest,

$$\frac{\delta P}{\delta K} \cong \frac{P_0 K}{j\omega} \frac{\left(1 + \frac{j\omega}{\omega_a}\right)}{\left(1 + \frac{j\omega}{\omega_1}\right)} \tag{16}$$

$$\omega_a \cong \lambda = 0.0829 \text{ rad/sec}$$

$$\omega_1 = \frac{1}{\ell^*} = \frac{\beta_{eff}}{\ell} = \frac{0.00855}{1.15\mathrm{X}10} \quad \text{rad/sec} \tag{17}$$

$$K = \frac{1}{11.85} \tag{18}$$

K was obtained by a trial and error technique from Figure 1 of Ref 17, as follows:

(19)

(71.1 corresponds to the generalized $\frac{1}{\ell^*}$ used in the analysis in Ref. 17)

let $\omega = 10$

$$\frac{120K}{10(1.01)} = 1$$

$$K = \frac{1}{11.85}$$

let $\omega = 100$, $K = \frac{1}{11.85}$

If one changes to

$$\frac{\delta P}{\delta K} = \frac{P_o/11.85 \qquad (1 + [1/.0829]j\omega)}{j\omega(1+[1/74.3]j\omega)} \qquad (20)$$

to allow for the experimental value of ℓ^*, the expression for K is still valid. Equation 20 is an asymptotic expression for the water boiler transfer function in the frequency range of interest.

E - COMPENSATED IONIZATION CHAMBER #1 (SERVAMP CIC)

Ref. 15 lists the transfer function as

$$K_I = 5X10^{-8} \text{ amp/watt}$$

F COMPENSATED IONIZATION CHAMBER #2 (Log N CIC)

The transfer function of this unit is not necessary for the loop analysis. This ionization chamber is located further from the reactor core than is chamber #1. However,

for flexibility of programming of the computer it may be assumed to have the same transfer function as CIC #1.

G THE LOG N AMPLIFIER

This unit has not been used in a control loop and the transfer functions from the input to the various outputs had to be determined experimentally. The RCL log N amplifier installed in the Water Boiler Control Console provides both LOG P and PERIOD signals to microammeters and strip chart recorders. It also provides a LOG P signal for use in driving a period amplifier. The problem is to adapt this unit for use in PERIOD and LOG P control loops.

Figure 5 shows the various outputs of the Log N amplifier. These outputs will be identified by connector (CN) number. The CN numbers used correspond to those shown in Radiation Counter Laboratory Drawing No. 20103-1 Log N Amplifier and in UCRL Berkeley Drawing No. 2PL1014A Pile Power and Period Meter Schematic.

Of the outputs shown in Figure 5, CN 8 was already in use in the period scram circuit and CN 11 was already being used with a power recorder.

1 LOG P CHANNEL

The time dependent parts of the transfer function to CN 10 and CN 11 are the same.

The transfer function may be derived from an expression for the output voltage of a Log N Amplifier in terms of reactor power, as given in Ref. 4. In terms of CIC output

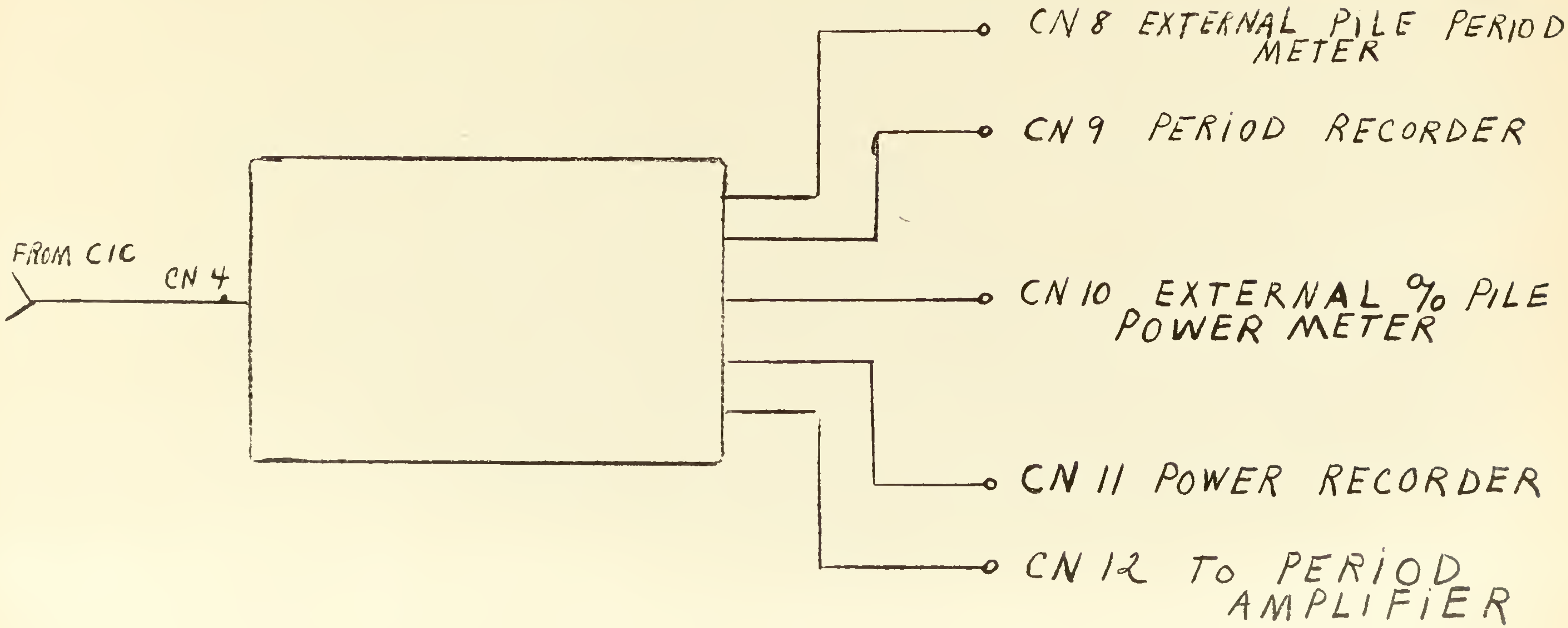

FROM CIC
CN 4
CN 8 EXTERNAL PILE PERIOD METER
CN 9 PERIOD RECORDER
CN 10 EXTERNAL % PILE POWER METER
CN 11 POWER RECORDER
CN 12 TO PERIOD AMPLIFIER

FIGURE 5

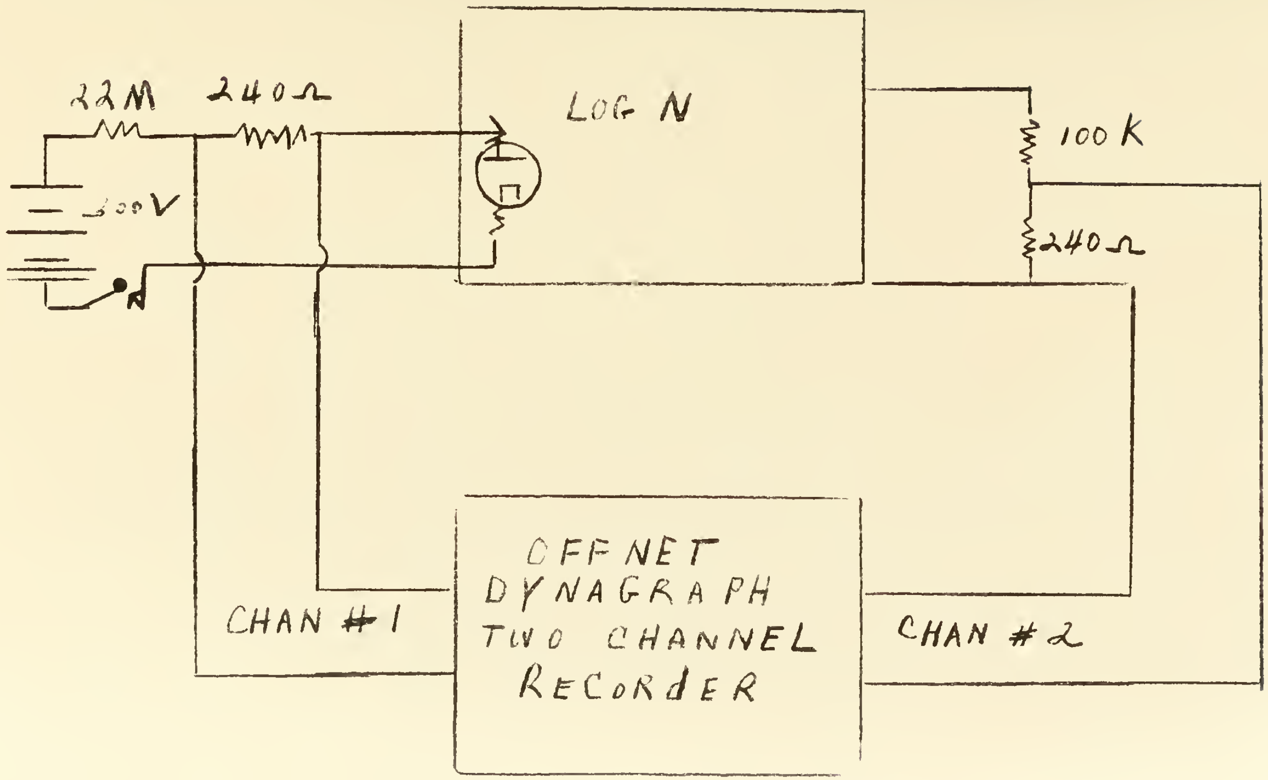

22M
240Ω
300V
LOG N
100K
240Ω
OFFNET
DYNAGRAPH
TWO CHANNEL
RECORDER
CHAN #1
CHAN #2

FIGURE 6

current instead of reactor power this expression is:

$$V_p(j\omega) = m \log \frac{I}{I_o} \; H(j\omega) \tag{22}$$

where I is the input current at CN 4

I_o is the extrapolated value of I at $V_p = 0$.

$$V_p + \delta V_p = \left[m \log \frac{I}{I_o} + \delta \left(m \log \frac{I}{I_o} \right) \right] H(j\omega) \tag{23}$$

$$\frac{\delta V_p}{\delta I} = \frac{m}{I} H(j\omega) \tag{24}$$

For determination of the frequency dependent part of the transfer function the equipment arrangement shown in Figure 6 was used (or slight modifications thereto for different scale factors involved at different outputs).

Figures 7 and 10 show unit step inputs and corresponding outputs at CN 12 and CN 10.

$$H(j\omega) = \frac{1}{1 + T_N (j\omega)} \tag{25}$$

$$t_r = \frac{1}{\omega_N} \tag{26}$$

$$\omega_N = 2\pi \times \frac{0.33}{t_r} \text{ rad/sec} \tag{27}$$

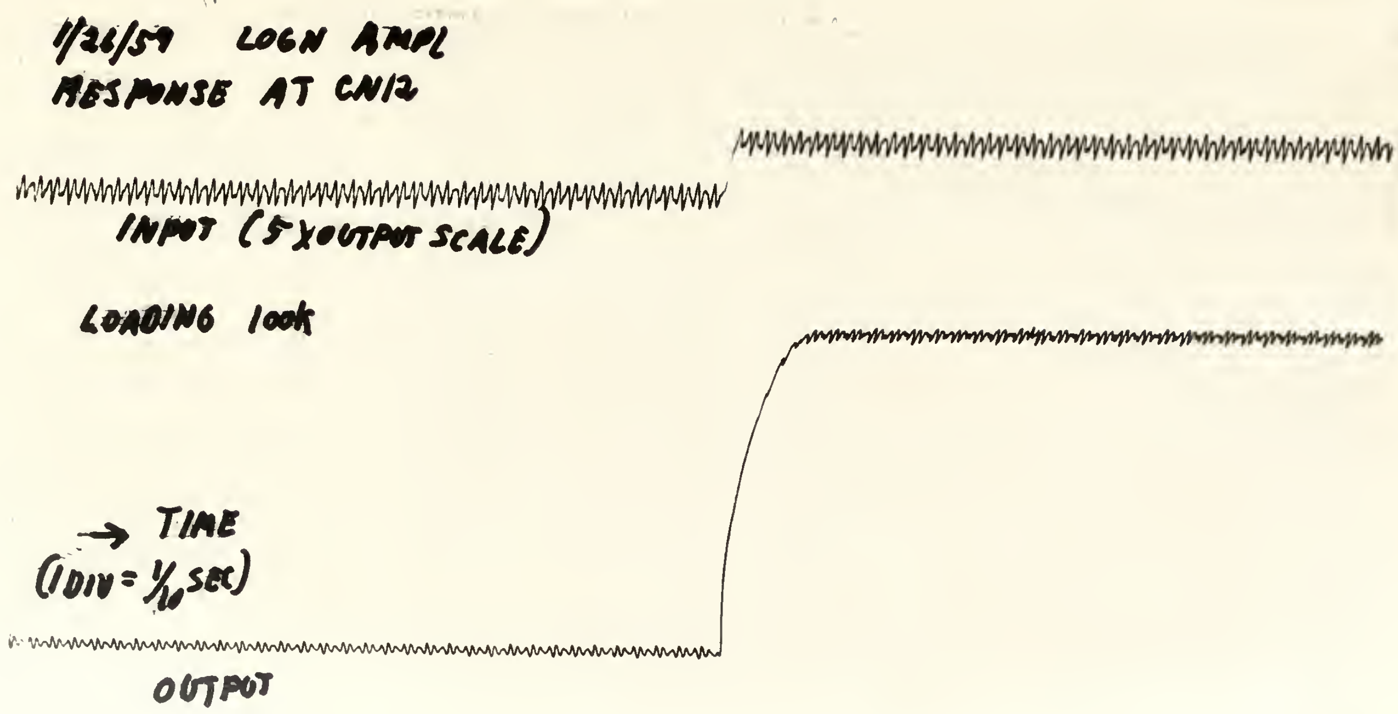
where t_r = rise time

$$\omega_N = 2.075 \left(50 \text{ mm/sec} \times \frac{1}{3 \text{ mm}} \right) = 34.5 \text{ rad/sec} \tag{28}$$

$$H(j\omega) = \frac{1}{\left(1 + \frac{j\omega}{34.5}\right)} \tag{29}$$

A measurement was also performed to determine the gain from CN 4 to CN 12 of the log N amplifier over the range of current input levels to which the amplifier is sensitive.

The arrangement of equipment is shown in Figure 8.


1/26/59 LOGN AMPL
RESPONSE AT CN12
INPUT (5 X OUTPUT SCALE)
LOADING 100k
→ TIME
(1 DIV = 1/10 SEC)
OUTPUT

FIGURE(7)

TABLE II

LOG N AMPLIFIER STATIC GAIN DATA SHEET

DATE 2/2/59

I IN amps	V OUT volts	% PWR MTR
2.98×10^{-9}	37	.00016
8.96×10^{-9}	43	.00025
2.69×10^{-8}	60.5	.0016
8.98×10^{-8}	96	.05
2.69×10^{-7}	114	.3
8.96×10^{-7}	129	1.5
1.55×10^{-5}	155	28
2.88×10^{-5}	165	70
5.0×10^{-5}	172	150

Calibration 50% on PWR MTR corresponds to 500W

12ND 6173

Figure 9 is a plot of the results.

Table II is the data sheet upon which Figure 8 is based.

The equation for the straight line approximation to the measured data shown in Figure 8.

$$y = mx + b, \quad x = \frac{y - b}{m} \tag{30}$$

In terms of the units of figure 8

$$V = \frac{\log I - \log I_o}{32} \tag{31}$$

$$I_o = 2 \times 10^{-10} \text{ amp} \tag{32}$$

$$V = \frac{1}{32} \log \frac{I}{I_o} \tag{33}$$

Therefore, from equation (24),

$$\frac{\delta V}{\delta I} = \frac{1}{32I} \qquad H(j\omega)$$

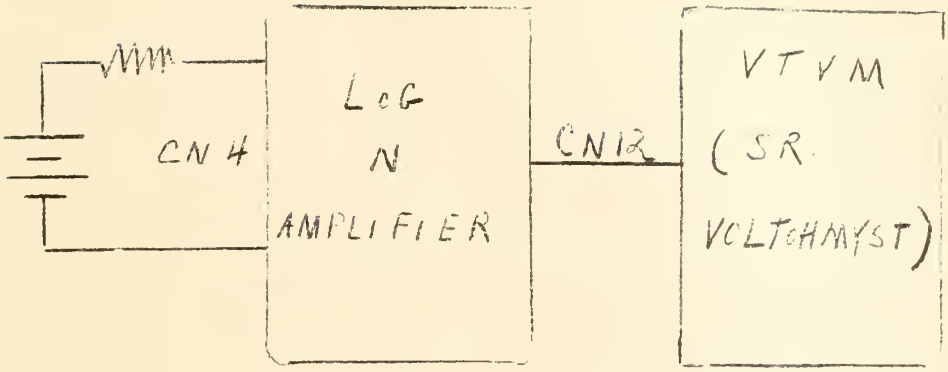
Thus the transfer function is:

$$\frac{\delta V}{\delta I} = \frac{1}{32I} \quad \frac{1}{(1+[1/34.5]j\omega)} = \frac{K_n}{I(1+T_\eta S)} \tag{36}$$

Figure 11 shows the effect of impedance changes at CN 10.

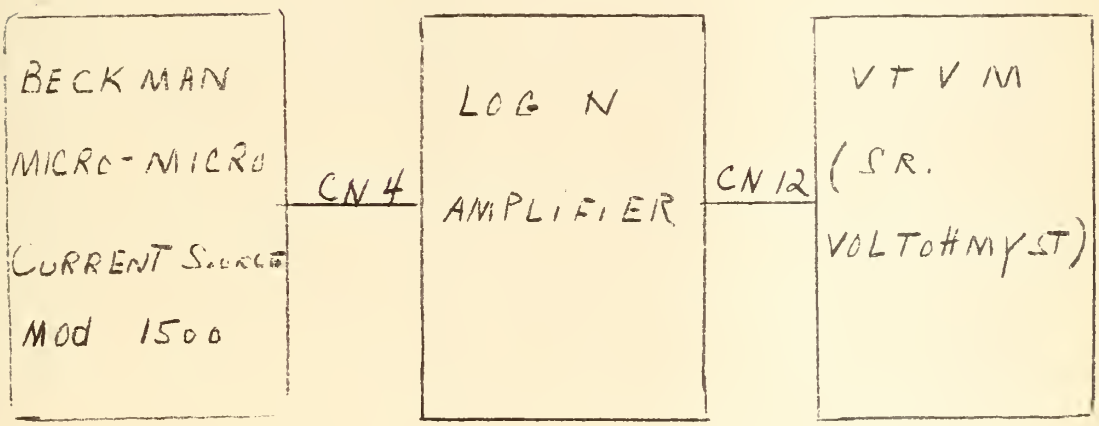
2. PERIOD CHANNEL

CN 8 and CN 9 are output connectors where a current or voltage proportional to the reactor period is available for use in a control loop. As indicated in Figure 12 the signal obtained at CN 8 or CN 9 is a function of any coupling impedance attached to these connectors. To reduce the effect of loading to a minimum, a high imput impedance (30,000Ω) Brown Amplifier - balance motor - retransmitting potentiometer



[INPUT CURRENT RANGE (10^{-6} TO 10^{-4})AMP]

(A)



[INPUT CURRENT RANGE (10^{-9} TO 10^{-6})AMP]

(B)

FIGURE 8.

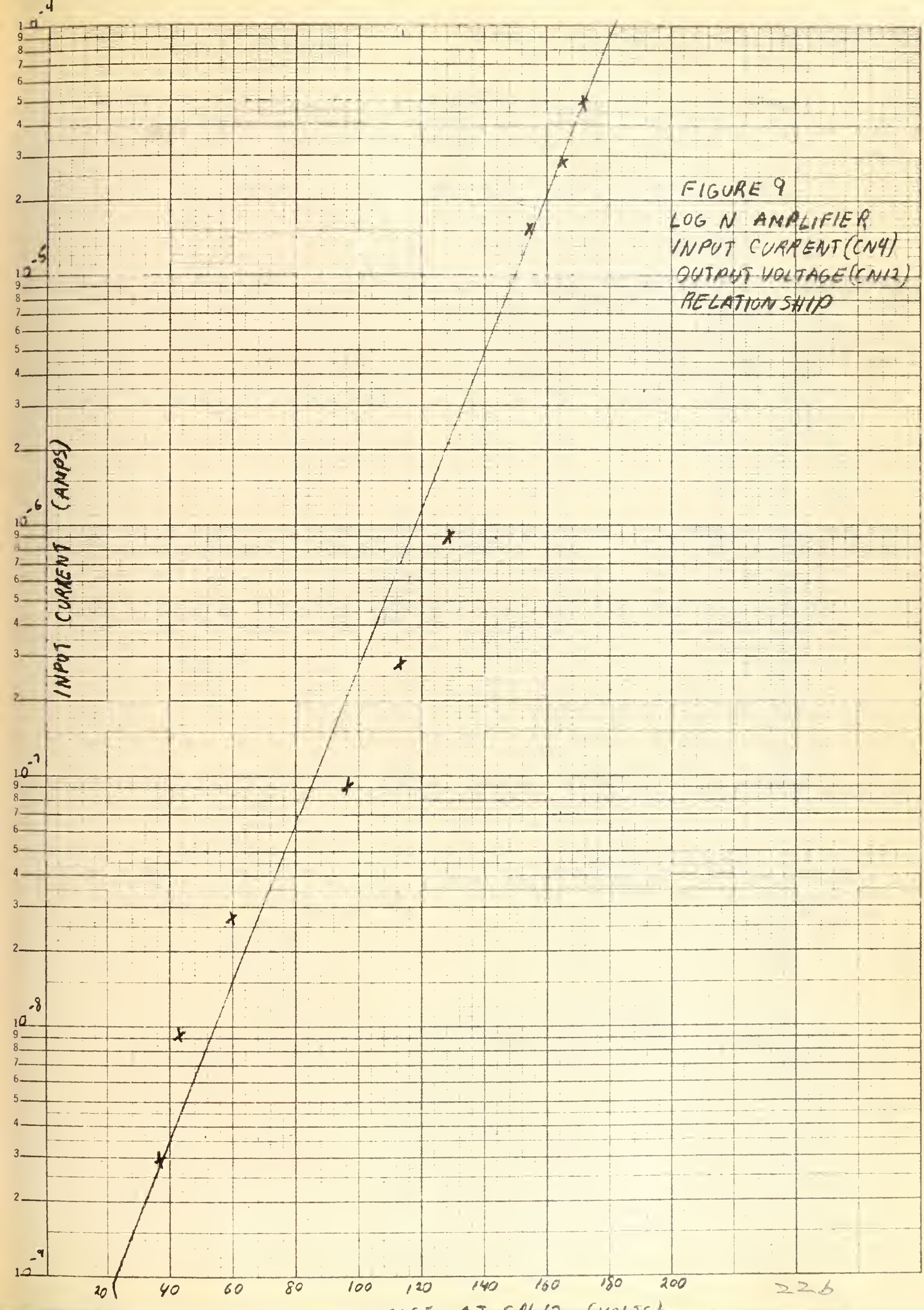


FIGURE 9
LOG N AMPLIFIER
INPUT CURRENT (CN4)
~~OUTPUT VOLTAGE (CN12)~~
RELATIONSHIP
INPUT CURRENT (AMPS)
OUTPUT VOLTAGE AT CN 12 (VOLTS)
20
40
60
80
100
120
140
160
180
200
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}

226

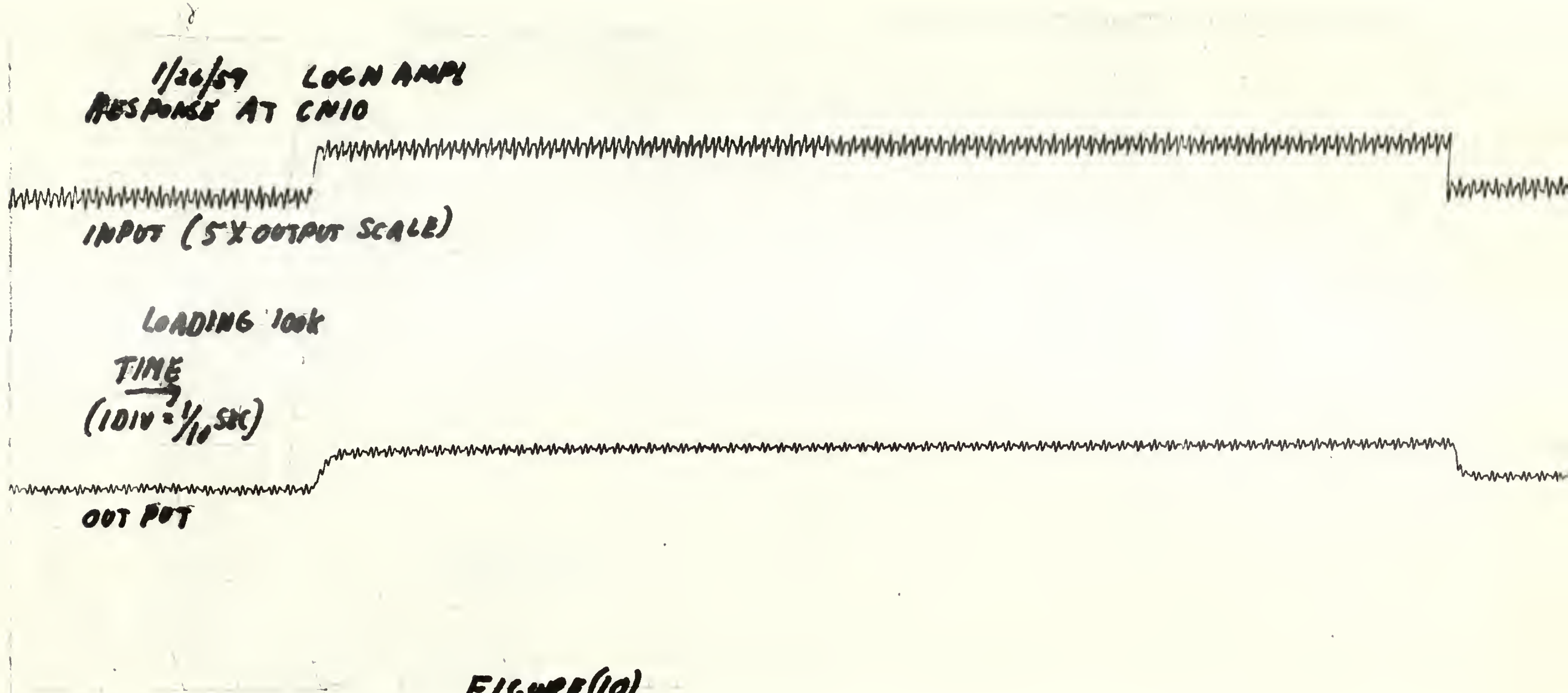

1/26/59 LOG N AMPL
RESPONSE AT CN10
INPUT (5 X OUTPUT SCALE)
LOADING 100k
TIME
(1 DIV = 1/10 SEC)
OUTPUT

FIGURE (10)

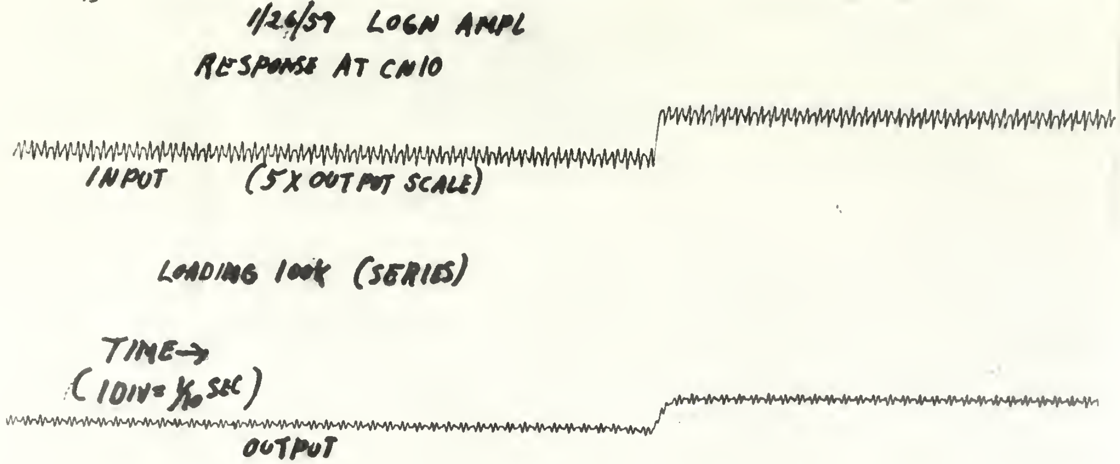


FIGURE 11(a)

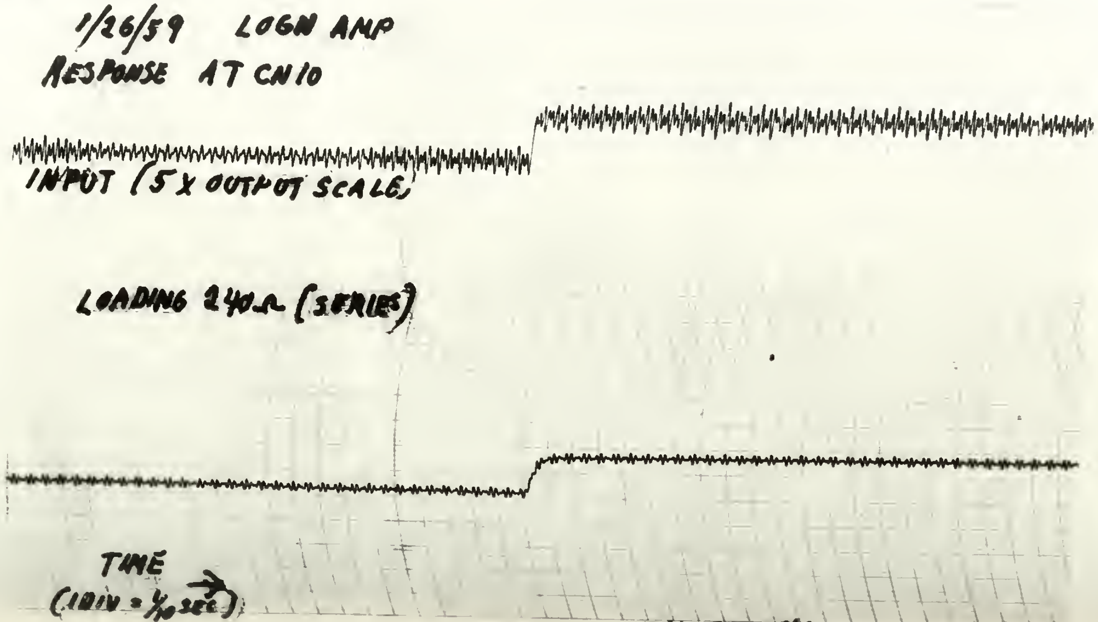


FIGURE 11(b)

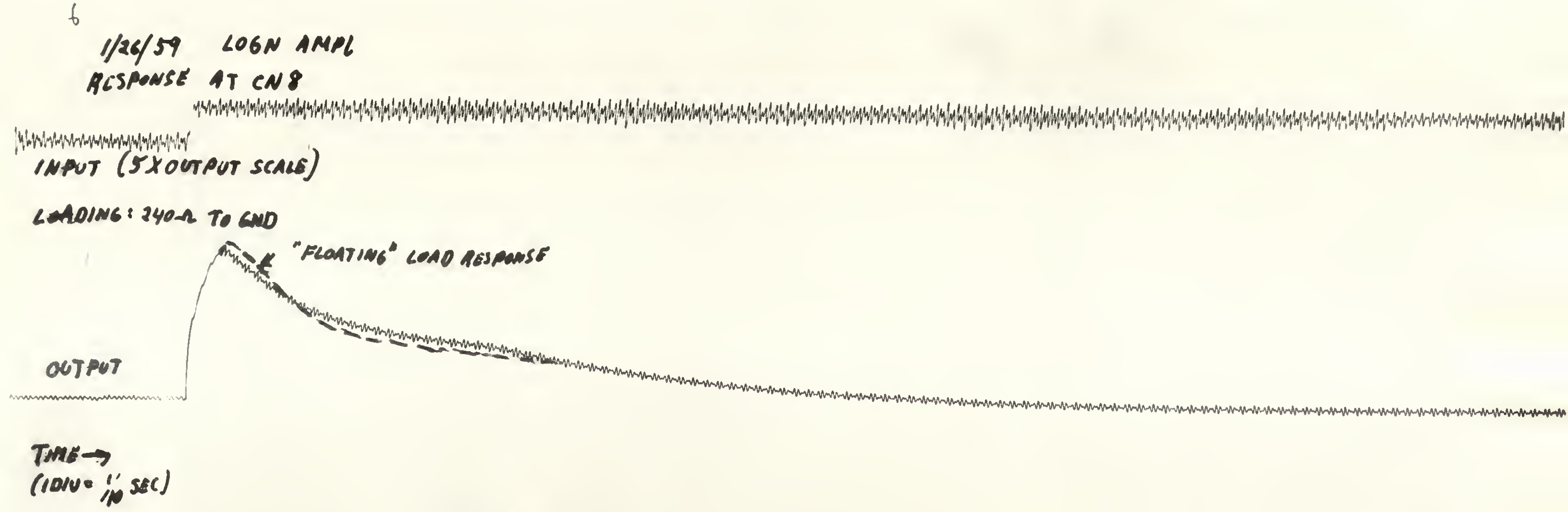


FIGURE 12(a)

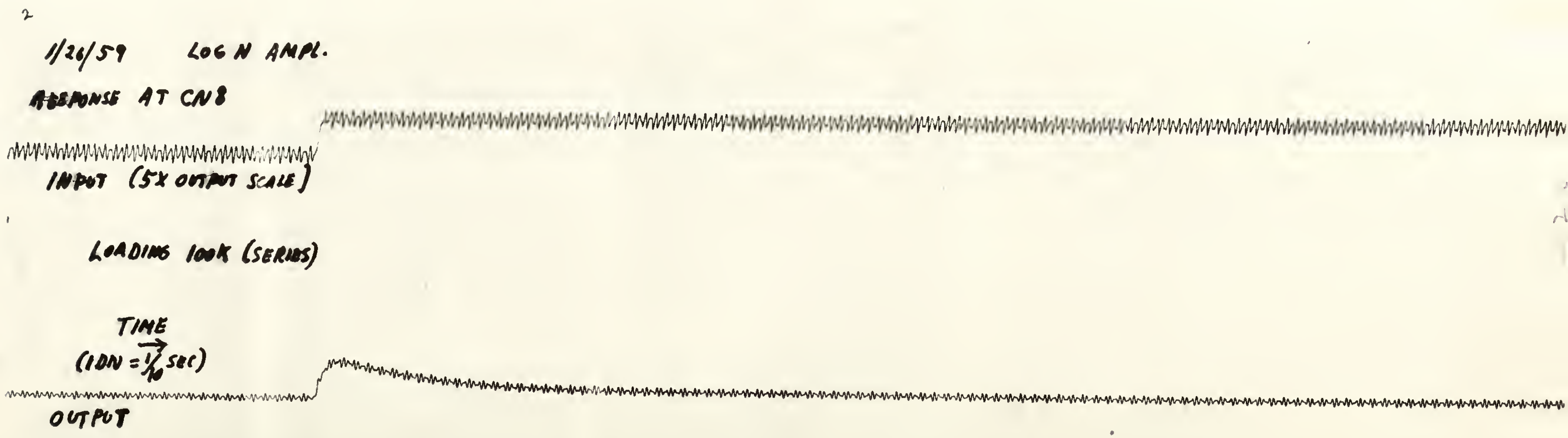


FIGURE 12(b)

will be used to couple the reactor period information to the period control loop. The frequency response of the amplifier-balance motor combination is considerably wider than that necessary for correct operation of the period control loop and therefore the amplifier-balance motor transfer function may be treated as essentially independent of frequency in the frequency range of interest. Moreover, the gain constant for the composite period detector may be set within limits by choice of retransmitting potentiometer output voltage.

In this composite period detector, then, the function of the log N amplifier is as follows:

t The log diode performs the operation,

$$V = k \log \frac{I}{I_o}$$

The voltage thus obtained, after suitable amplification, is subject to differentiation by an RC network. Figure 13 is a block diagram representation.

The transfer function for the first block has been shown to be of the form,

$$KG_1 = \frac{k_1}{I} = \frac{1}{1+T_dS} \qquad (37)$$

The transfer function for the second block is approximately that of a black box providing simple differentiation with a time delay,

$$KG_2 = \frac{k_2 S}{1+T_pS} \qquad (38)$$

Taking these blocks in cascade, the overall transfer function is:

$$KG = \frac{k_3 S}{I(1+T_dS)(1+T_pS)} \qquad (39)$$

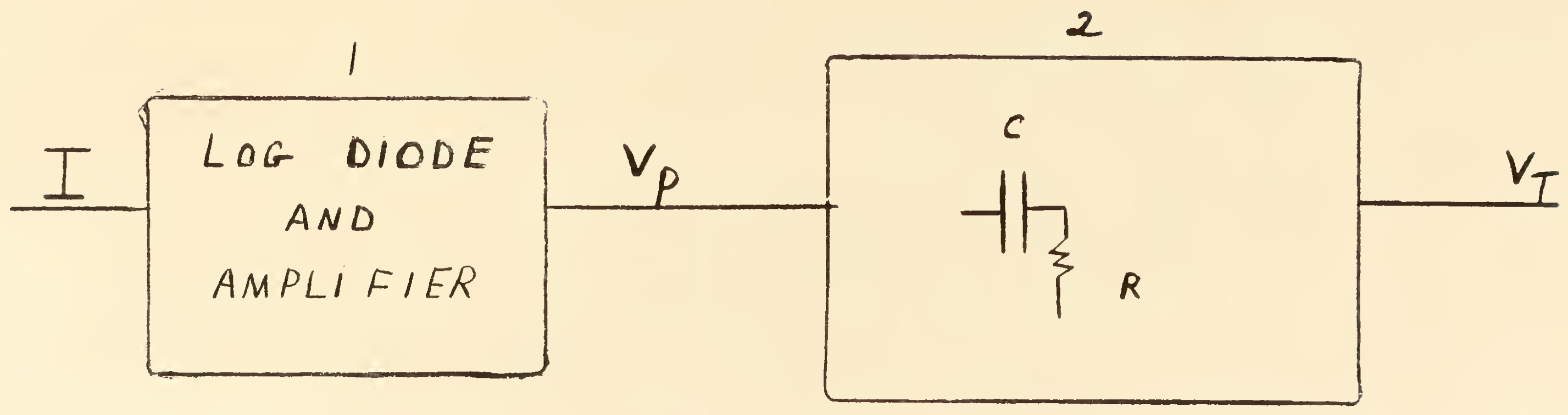


FIGURE 13

Before evaluating the gain constant for the composite detector, first consider the ideal case of no time delays in the Log N amplifier.

Recall that

$$V_p(t) = k_4 \log \frac{I}{I_o}(t) \tag{40}$$

and that

$$T = \frac{P}{dp/dt} = \frac{I}{dI/dt} \tag{41}$$

where T = REACTOR PERIOD

since

$$V_T \overset{D}{=} \frac{dV_p}{dt} \tag{42}$$

then

$$V_T = \frac{k_1}{I} \quad dI/dt = \frac{k}{T} \tag{43}$$

that is, the output voltage of the differentiator in the ideal case is inversely proportional to the reactor period.

Since the gain of the coupling network is a constant, it follows that the output voltage of the composite period detector is proportional to the inverse reactor period.

The effect of the exponential time delays in the log N, therefore, is to degrade the period measurement so that the output voltage of the composite period detector is proportional to an indicated inverse reactor period, which approximates the true reactor period.

Based upon linear analysis considerations of loop gain and speed of response, the output voltage was taken to be

0.05 volts, to correspond to a 30 second reactor period. Thus equation (39) may be written,

$$KG = \frac{\text{output}}{\text{input}} = \frac{.05 \text{ volts}}{I} = \frac{ks}{IT_1} \qquad (44)$$

$$\therefore \quad 0.05 = \frac{k}{T_1 \, (S)} \qquad (45)$$

where T_1 (S) = 30 sec = indicated reactor period.

$\therefore$ k = 1.5

$$KG = \frac{1.5S}{I(1+T_pS)\,(1+T_dS)} \qquad (46)$$

Alternatively, if we consider I = I (t,T), by partial differentiation we may establish the gain constant is a function of T.

$$\left.\frac{\partial V}{\partial I}\right]_{t=const} = -\frac{k_1}{I^2}\frac{dI}{dt} = -\frac{k_1}{IT} \qquad (47)$$

The minus sign is removed by the choice of an odd number of stages of amplification in the log N, and the gain of the transfer function is again seen to be inversely related to the reactor period.

Thus it is evident that automatic period control may provide an additional safety feature. By proper choice of the maximum period demand voltage which may be programmed, the designer restricts the shortest period which may be demanded of the reactor. This design consideration is discussed further in Appendix IV. It is noted here that this prevents the operator from inadvertently positioning the fine rod so as to demand too short a period.

In evaluating the frequency dependent part of the transfer function an arrangement of equipment similar to that shown in Figure 6 was used. Figure 14 shows the response of the Log N Amp. at CN 8 to a step input at CN 4.

From the form of eqn. (44), it is evident that two time constants need to be determined. These time constants were determined from Figure 14.

Figure 15 is a sketch of the summation of exponentials contributing to the response.

Analytically, this represents a sum of the form,

$$V = K_1 e^{-\frac{t}{T_d}} + K_2 e^{-\frac{t}{T_p}} \qquad (48)$$

where the K_i are of equal magnitude but of opposite sign.

T_d and T_p are the times required for these factors to reach 37% of their final value.

From Figure 11:

Intercept of (t = 0) is 7.8 cm

7.8 X.37 = 2.88

T_d (45mm) = .9 seconds

T_p (2mm) = .04 seconds

From which

$$H(j\omega) = \frac{j\omega}{\left(1+\frac{j\omega}{1.11}\right)\left(1+\frac{j\omega}{25}\right)} \qquad (49)$$

$$KG(j\omega) = \frac{1.5\, j\omega}{I\left(1+\frac{j\omega}{1.11}\right)\left(1+\frac{j\omega}{25}\right)} \qquad (50)$$

Several design decisions have to be made before the system synthesis can proceed. Listed below are several

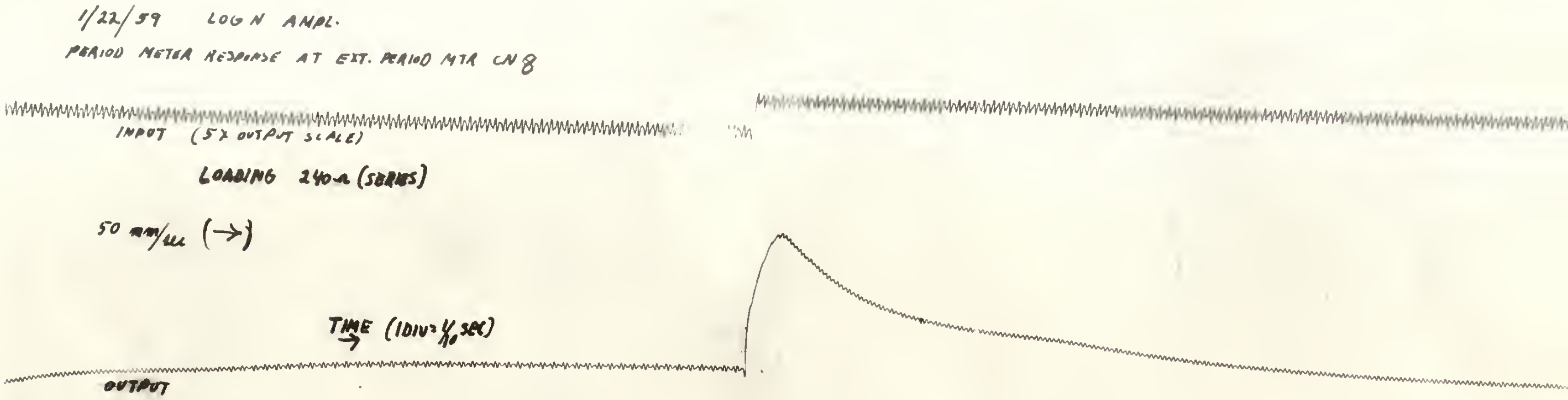

1/22/59 LOG N AMPL.
PERIOD METER RESPONSE AT EXT. PERIOD MTR CN 8
INPUT (5 x OUTPUT SCALE)
LOADING 240 Ω (SERIES)
50 mm/sec (→)
TIME (1 DIV = 1/10 sec)
OUTPUT

FIGURE 14

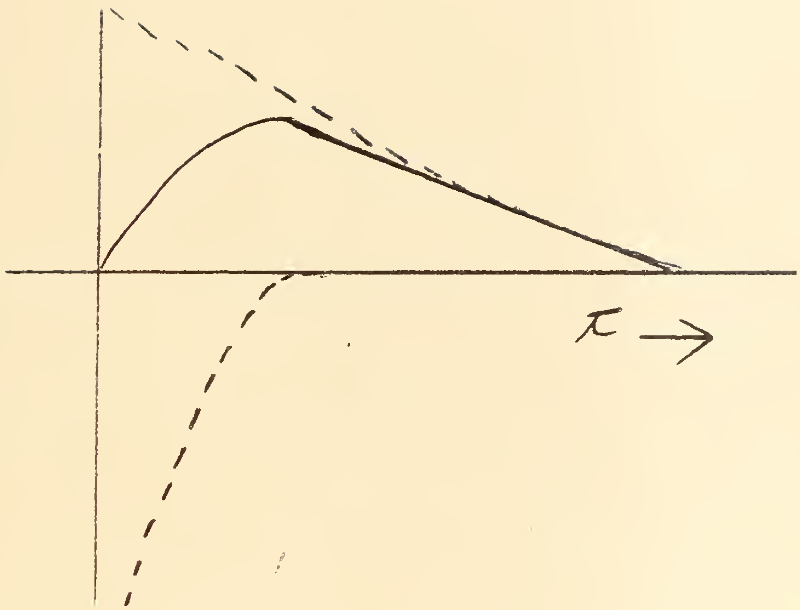


FIGURE 15

alternatives considered with reasons pro and con or design considerations listed.

POSSIBLE MODES OF CONTROL

Control of Coarse Rod and Fine Rod

1. Relatively large amounts of reactivity available for control.

2. Involves extensive modification of coarse rod control system for full automation of coarse rod.

3. System normally used in control by human operator.

Control of Fine Rod Only

1. Less reactivity available than with coarse and Fine Rod control.

2. Servo Control Motor and Amplifier are already installed, the amplifier will have to be modified.

3. Insufficient reactivity available to control loop to make reactor prompt critical.

Control by other means such as control using temperature coefficient of reactivity.

1. Extensive Preliminary Research is involved.

2. Extensive changes in present equipment may need to be made.

3. Several safety considerations are unknown.

4. All design objectives could not be met.

SELECTED MODE OF CONTROL

Find Rod Control was chosen. However, a modified form

of Coarse Rod - Fine Rod Control was experimentally evaluated.

In imitation of the human operator, it was decided that after the coarse rod had been withdrawn to a fixed position by the operator, the fine rod should be automatically withdrawn until a predetermined count rate was achieved, at which time the rod would be stopped and the reactor allowed to rise in power until sufficient information became available for period control.

This method has the advantage of long term temperature feedback, in that the predetermined count will not be achieved until a certain excess reactivity exists in the reactor if the fine rod is withdrawn at a constant rate.

For example, the reactor may be started up with an initial core temperature of 49°F or if the building temperature is higher, the initial core temperature at startup may be 55°F. In the latter case it is necessary to withdraw more of the fine control rod in order to achieve the supercritical condition than in the former case.

Essentially, this method provides control of power level at which the rod is stopped. The optimum control would be continuous control of rate of rise of power level, but instrumentation is not available in the source range to provide this information.

This method is referred to a INITIAL ROD DRIVE in this paper.

A third method would be programming the initial rod motion by means of a computer control device as is done

with Tory II. This requires instrumentation not readily available, however.

In the period range it was decided to use period control or automatic Log P control in order to evaluate these modes of control.

In the power range both Log P and Lin P control was designed into the system in order to meet design requirements. Lin P control is a proven control method. Log P control was incorporated to assist in Tory II Design Philosophy evaluation.

A multimode controler aspect was included to allow automatic switching from one mode of control to another.

FEATURES OF THE MULTIMODE CONTROLLER:

The multimode controller required the design of new circuitry in order to effect switch-over from one control loop to another at the times desired.

To allow for the demanding of any power level, it was decided to switch from one control loop to another using Log P Error information. This information is available over the power range and most of the period range.

A device to effect this switch-over was designed using transistor circuitry. However, in order to allow more flexibility this device was abandoned in favor of another circuit designed around Symplytrol* Relays. Nevertheless, it is felt that the transistor circuit is potentially a useful one in reactor control.

* Trademark Assembly Products Corp

Among the features incorporated in the multimode controller is a selector switch whereby prior to startup, the operator may select the control loops he desires to use in startup.

If startup is to be from source level the startup sequence may be Initial Rod Drive-Initial Rod Drive Stop-Period Control-Lin P Control, or Initial Rod Drive- Initial Rod Drive Stop-Period Control-Log P Control.

If the reactor is operating at some power level P_1 and it is desired to increase power to P_2 where P_2 is greater than P_1, the modes of control available are Period Control - Lin P Control or Period Control-Log P Control. Such is the case on restarts from the period range.

If the reactor is operating at some power level P_1 and it is desired to decrease power to P_2 where P_2 is less than P_1 the modes of control available are Log P, or Lin P to Log P to Lin P.

For power changes on periods faster than 50 seconds there is provision for a "period run up" just prior to reaching the demanded power level to prevent overshoot in power level. The power level, at which period is increased, is adjustable as is the new demand period.

The major controlling signal in switch-over points is the Log P error signal. By controlling the switch-over point from Per to Lin P or Per to Log P on the Log P error signal and switching at very slightly above demanded power (LIN P), the initial motion of the control rod will always be inward.

This is similar to the procedure used by the operator when switching from manual to automatic control using the linear power set.

Control may be taken away from the automatic controller at any time by the operator throwing the auto-manual switch on the Reactor Control console to manual.

COMPARATOR AND METER-RELAY CIRCUITS

The basic comparator circuit is that of a simple null type phase sensitive detector modified to meet the needs of the control loop in which it is installed. It is shown in Figure 16.

As pointed out in Ref 19, the relation

$$\frac{R_1}{R_a} = \frac{R_2}{R_b} \qquad (51)$$

should be maintained for best performance and accuracy unless R_a and $R_b \gg R_1$ and R_2 . Symbols refer to Figure 16.

The null type detector shown in Fig. 16 was chosen because of its common terminal feature and because it is phase sensitive.

A - PERIOD CHANNEL COMPARATOR

Some factors considered in the design of the period channel error detector are:

1. Type of Potentiometer available for mounting on the Brown Recorder Mechanism.

2. Power supplies available.

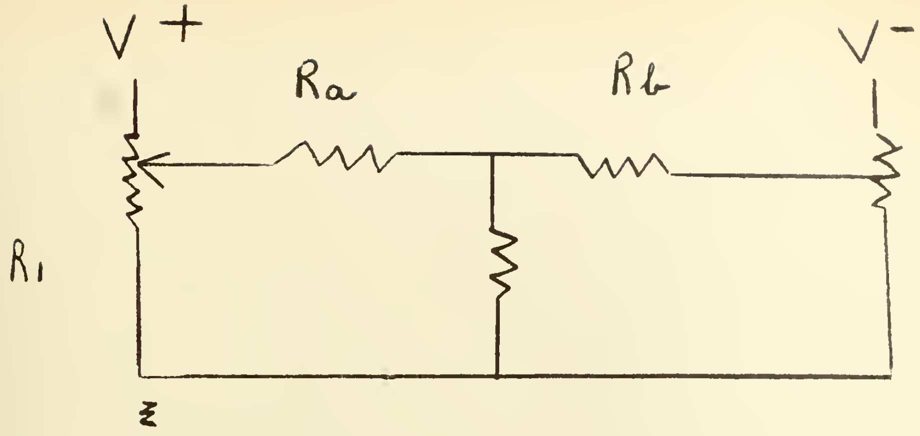
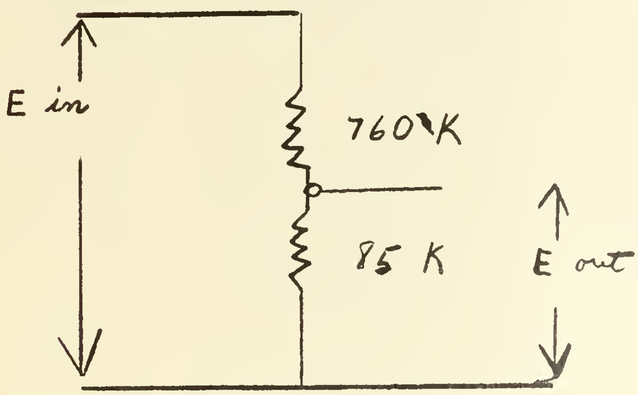


FIGURE 16

TRANFER FUNCTION OF PERIOD CHANNEL ERROR DETECTOR



$$\frac{E_{out}}{E_{in}} = \frac{85}{85 + 760} = \frac{1}{10}$$

FIGURE 17

a. Positive and Negative Supplies

b. Power Output

c. Voltage Output

d. Voltage Regulation

3. Servo Amplifier Requirements.

a. Optimum source impedance

b. Range of error voltage

4. Possible shielding requirements for handling low level signals in high impedance circuits.

5. Error Detector Requirements.

a. Optimum R_1 to R_a ratio

b. Power handling ability

c. Precision of components needed

d. Mechanical design features

6. Loop Transfer Functions.

a. Effect of detector gain on system stability and response speed.

7. Effect of Multimode Controller

(See Figure 17)

8. Period Runup

This is accomplished by shunting the Demand Period Potentiometer by a resistance at the appropriate time in the startup sequence. This is designed to give the same runup period for various Per Demands.

B LOG P CHANNEL COMPARATOR AND METER RELAYS

Many of the factors considered above were also necessary considerations here.

TABLE III

VERSATROL DATA

Relay Designation (Figure 18)	Range	Load Relay Contact Rating	Contact Arrangement	Coil Arrangement	Size	Remarks
1	0-200 μa DC	110V AC, 250ma	Low Limit Single Contact Adjustable Man. Reset	Isolated Coils	351 C	1. In original model range 0-50 microamp, only was available and used for all meters.
5	0-200 μa DC	110V AC, 250 ma	Low Limit Single Contact. Adjustable Manual Reset	Isolated Coils	351 C	2. In original model Versatrol load relay circuits were not available and substitute circuit shown in Fig. 20 was used.
8	0-200 μa DC	110V AC, 250 ma	High Limit Single Contact Adjustable Auto. Reset	Isolated Coils	351 C	
10	0-50 μa DC	110V AC, 250 ma	High Limit Single Contact Adjustable Manual Reset	Isolated Coils	351 C	3. Size 451 C only was available and control chassis front panel was modified accordingly.
11	0-50 μa DC	110V AC, 250 ma	High Limit Single Contact Adjustable Manual Reset	Isolated Coils	351 C	

In addition the design of multimode controller units and their effect on the error detector had to be considered here. The detector is shown in Figure 18. (Figure 18 is the schematic for the experimental control system.)

Meter shunting diodes were used to allow the use of a sensitive meter for small error signals and to allow relatively large currents to pass through the diode shunts.

Blocking series diodes were used to protect the meters against signals of the phase opposite to that for which the meter was designed to indicate. Suppressed zero meters had been considered but were not satisfactory for this application.

Type 1N-205 diodes were chosen on the basis of a very high front to back ratio, current handling capability, peak inverse voltage requirements, and availability.

Resistors were chosen consistent with the components already chosen and external requirements on the error detector.

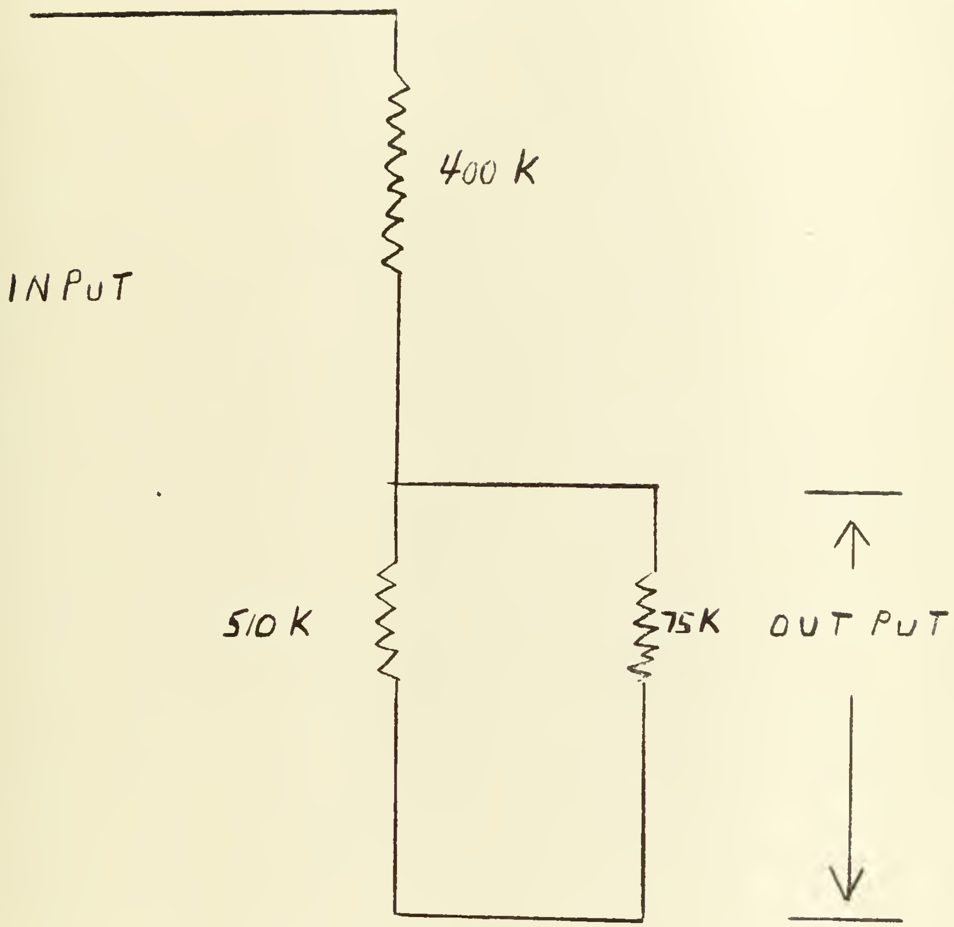
Versatrol relay data is tabulated in Table III.

The log P error detector shown in Figure 18 was designed allowing for a maximum 10:1 decrease in signal level. The actual attenuation achieved may be computed approximately from the equivalent ckt. shown in Figure 19.

C. INITIAL ROD DRIVE CHANNEL ERROR GENERATOR & METER RELAY CIRCUIT

The initial rod drive error signal source is merely a modification of the basic null type detector.

The CRM meter relay circuit is a slightly modified ver-



$$K_{AN} = \frac{65}{400} = .163 = 1.63 \times 10^{-1}$$

FIGURE 19

sion of a meter circuit specified by the CRM instruction manual for the use of an external meter with the CRM. Again, the shunting diode allows use of a more sensitive meter.

D LOG N METER RELAY CIRCUIT

The log N meter relay circuit is patterned on the CRM detector with the change that a 1N-34 diode is used instead of a 1N-205. The less-severely-non-linear characteristic, and higher current handling ability of the 1N-34 provides better protection for the meter which is operated offset below 0 dial divisions part of the time.

The "Meter Load Relay" circuit shown in Figure 20 was designed by Mr. Bob Marshall of Livermore Radiation Lab as a substitute for similar Versatrol units which were not immediately available.

Many of the design considerations entering into the design of the Power Relay Circuitry shown in Figure 18 are mentioned in the description of relay operation which follows.

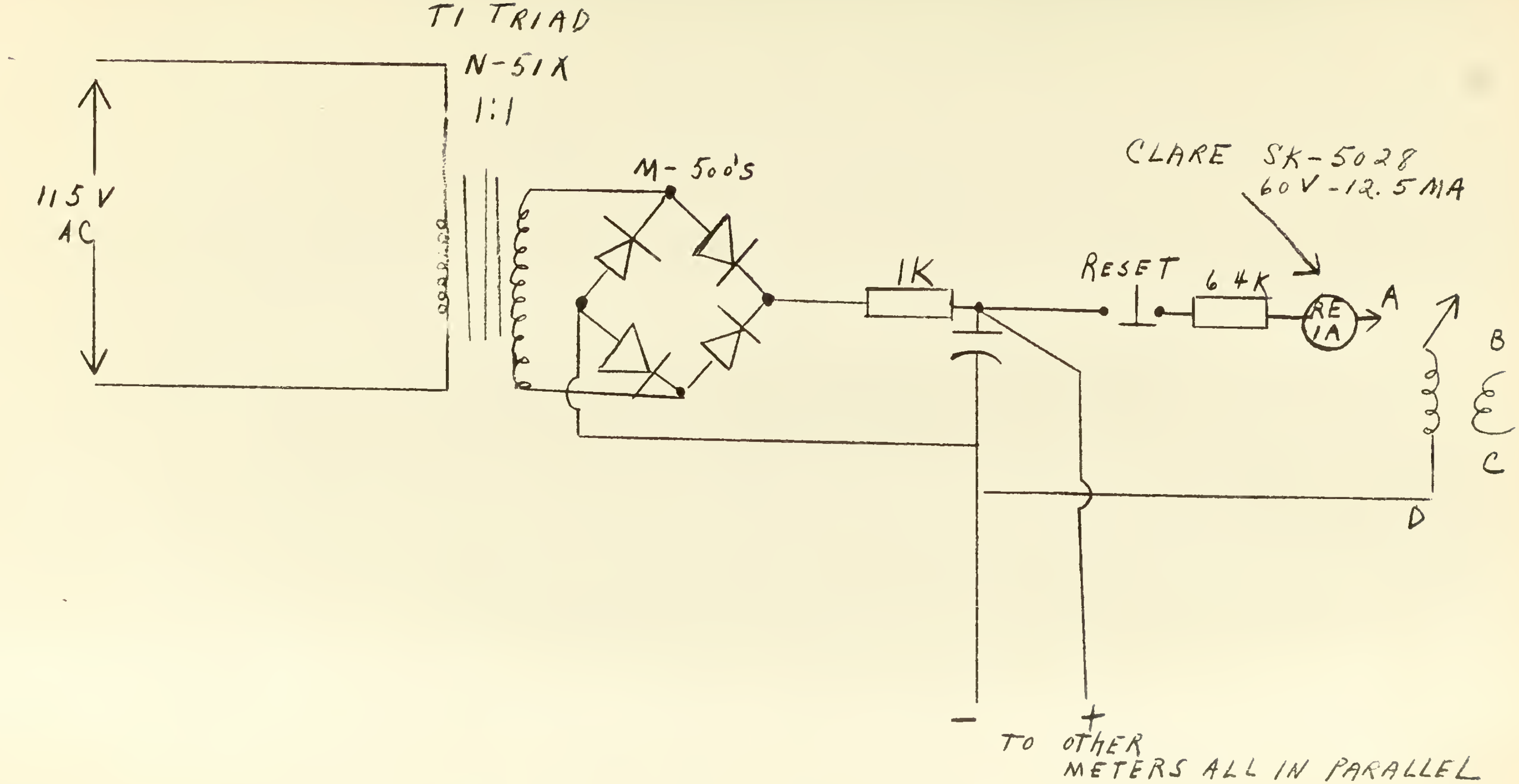
MULTIMODE CONTROL - OPERATOR PROCEDURE AND RELAY SEQUENCES

A ID-PER-LIN P SEQUENCE (Cold Startup)

The operator turns on DC power, then AC power, and selects Lin only on the Mode selector switch. He then checks that all sensitrol relays are reset. If necessary, he resets the relays by pushing the appropriate reset button.

It is assumed that all reactor console checks have been completed and that the initial rod rate demanded period and demanded power levels have been set on the Auto Controller and Servo Amplifier and corresponding limit contacts have been set. (With repeated operation, these controls may be left set at the normally used positions).

The operator manually withdraws the safety rods and



METER LOAD RELAY CIRCUITS (MLRC)

(DESIGNED BY MR BOB MARSHALL OF UCRL) (TEMPORARY REPLACEMENT FOR VERSATROL UNITS.)

FIGURE 20

coarse control rod. (Appendix III Discusses as yet untested circuitry to automatically accomplish this function). He then turns the Auto Manual Switch on the Reactor Control Console to Auto.

Turning on the AC power causes the following events:

1. Turns on AC "power on" light (white)

2. Energizes relay 12. Relay 12 is a fail-safe feature. If relay 12 is deenergized a net error voltage is applied to the servo amp which causes the fine control rod to move all the way in.

3. Energizes relay 3. This relay action connects the initial rod drive channel to the servo amplifier. This is a fail-safe feature in that positive action is required to allow fixed error drive of the fine rod.

4. Energizes relay 7. This allows the period channel to be used later. This is a fail-safe feature in that positive action is required to allow period control.

5. Turns on Initial Rod Drive Light (Red) in conjunction with action of relay 7. This light indicates present mode of control.

Switching to Automatic initiates the following sequence:

Connected the output of the servo amplifier to the servo control motor which allowed the fixed error signal from the initial rod drive channel to start moving the fine rod out.

A signal from the Fission Chamber Channel causes Symplytrol relay RE 11 to make contact with the upper limit set.

This actuates Load Relay RE 11A which actuates RE 4, and turns on Initial Rod Drive Stop Light (LT 3 Red).

Relay 4 opens the Initial Rod Drive Channel and applies a short circuit-ground across the input to the Servamp causing the fine rod to stop.

A signal from the Log N amplifier (CN 8) causes Symply-trol relay RE 10 to make contact with the upper limit set. This actuates load relay RE 10A which turns on PER Control Light (LT 4 Red), and also actuates RE 2.

Relay 2 deenergizes relay 3 and relay 4 and turns off LT 3 and LT 2. By deenergizing relays 3 and 4, relay 2 connected the PER Channel to the Serv Amp.

The fine rod is moved by the error signal so that the reactor period is adjusted to the demanded period.

If the period run-up feature is being used, when the Log P error signal reaches a pre-set level, Symplytrol relay RE 1 makes the lower limit contact which actuates RE 1A which shunts across the Period Demand pot a resistance, thus increasing the demanded period. The reactor adjusts to the new demanded period. The amount of resistance in the shunt is controlled by a screw driver adjustment on the rear of the Auto-Controller chassis.

When the reactor power level is very slightly above the demanded power, Symplytrol relay RE 5 makes the lower limit contact. RE 5 energizes RE 5A which energizes RE 6 and deenergizes RE 7.

Deenergizing relay 7 disconnects the Per Channel from the Serv Amp and Connects the Log P error channel to the

Serv Amp. It also turns off Lt 4.

RE 6 turns on Lin P control light 6 and disconnects the Log P Channel from the Serv Amp and connects the Lin P Channel to the Serv Amp. RE 6 also disconnects the semi-fixed gain section of the Serv Amp.

The fine rod moves so as to level off the reactor at the demand power level.

In this mode of control, RE 8 acts as a safety feature. If the log P error changes sign and increases Symplytrol RE 8 upper limit contact makes. This energizes RE 8A which energizes RE 9 which deenergizes RE 7, putting the reactor on Log P control. In this case RE 9 also turns on Log P control light 5 (yellow). This action of RE 8 is solely a back stop type of action and does not occur in normal operation of the Per - Lin P Control Mode.

B ID-PER-LOG P SEQUENCE (Cold Startup)

The operator turn on DC power, then AC power and selects Log only on the Mode Selector Switch. He then proceeds as in a Per - Lin P startup.

Relay and Light Sequence is the same up to the point where Symplytrol Relay RE 5 makes the low limit contact. This energizes relay 5 A which now has no effect.

The log P error signal reduces to zero and changes sign as the reactor power level becomes very slightly above that demanded by the Log P Demand Setting. This action makes Symplytrol relay RE 8 upper contact which energizes relay 8A which energizes relay 9.

Relay 9 deenergizes relay 7 which connects the Log P error signal to the Servo Amplifier with the error of such polarity as to cause the fine control rod to always initially move inward. Relay 9 also turns on Lt 5 which indicates Log P Control.

C - RESTARTS

1. Any restart from the source range is the same as a cold start in so far as the automatic control system is concerned.

2. A restart from the lower part of counter range automatically, requires that RE 11 upper limit contact be reset 3 scale divisions above the count rate level indicated at the time of Restart. This Figure of 3 scale divisions was experimentally determined and is subject to correction as the result of additional experimental evaluations.

3. A restart from the upper part of the counter range may be accomplished in theory by resetting the range switch on the controlling CRM and proceeding as if on the lower part of the counter range. However, in practice, it has been found safer to not restart from the upper part of the counter range and to remove the range switch from the controlling CRM because of the possibility of operator error in setting the switch on too high a range for an initial start-up.

4. A restart from the period range, the most usual case, is achieved by merely <u>not</u> resetting relay 10 prior to placing the system in automatic control.

In any restart, the relay sequence will be the same as

from a cold start with the one difference that some part of the relay sequence will have been effectively completed prior to restart.

D - POWER LEVEL RUNDOWN

If the reactor is operating at some power level in Lin P control, the operator may select the Lin - Log mode of operation and reduce power over several decades using Log P control.

Prior to selecting Lin Log control, the operator sets the Log P Demand Pot at the new demanded power level.

When the operator switches to the Lin Log mode of operation, relay 8 upper limit contact makes, provided the new power level is significantly less than the original power level. (If it is not, the reactor remains on Lin P control which is adequate for small power decreases.) Relay 8 energizes relay 8A which energizes relay 9 which turns on Lt 5 and simultaneously relieves relay 5A of the burden of maintaining relay 7 deenergized. Relay 9 also deenergizes relay 6 and turns off light 6, thus putting the reactor in log P control.

An additional feature, yet to be tested experimentally, provides automatic reset action of RE 8 when in Lin Log control mode. This will allow the reactor to be brought to a lower power level on Log P control and automatically placed on Lin P control when at the lower power level. It is necessary to reset the Lin P demand pot to the new power level in the interval that the reactor is reducing power on Log P

control, or at the expense of additional complexity in design, a second linear P Demand Potentiometer could have been added to allow the operator to make all settings before initiating the sequence. Either scheme requires a Versatrol automatic reset feature and an additional sections on the Mode Selector switch to provide for use of this auto reset in the Lin Log mode only.

If the Log mode of control has been selected, the power level may be reduced to any new power level by merely resetting log P Demand Pot. Since Lin P control ohly functions in the range 1 W to 500 Watts, the Log P mode of control has found application in the range .02 W to 1 W where it has experimentally shown satisfactory control characteristics as well as in the range 1 W to 500 W.

CONTROL LOOP ANALYSIS:

A. INITIAL ROD DRIVE-STOP CHANNEL

This control loop contains a non-linear element, the relay. The feedback channel is not used in the ordinary sense as part of a continuous or sampled data closed loop. The feedback loop merely serves to switch once in the startup sequence from one forward control loop (the initial rod drive channel) to another, the initial rod drive-stop channel. Nevertheless, the block diagram shown in Figure 21 does illustrate the advantage of feeding back a count rate instead of control rod position; i.e., the amount of negative reactivity which must be removed to make the water boiler supercritical

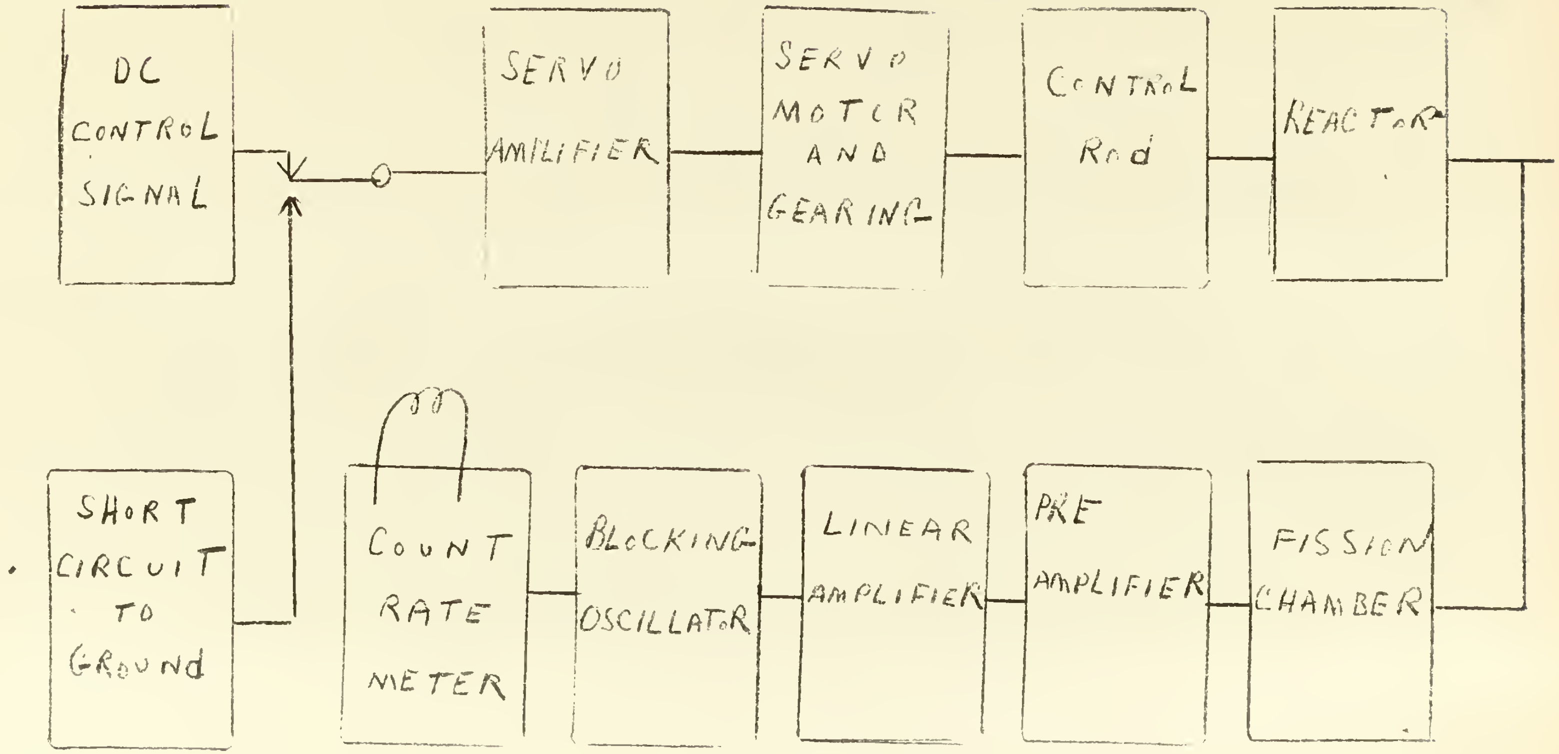

DC CONTROL SIGNAL
SERVO AMILIFIER
SERVO MOTOR AND GEARING
CONTROL Rod
REACTOR
SHORT CIRCUIT TO GROUND
COUNT RATE METER
BLOCKING OSCILLATOR
LINEAR AMPLIFIER
PRE AMPLIFIER
FISSION CHAMBER

FIGURE 21

is quite dependent on core temperature at the time of startup.

The instrumentation from fission chamber to CRM is a standard UCRL arrangement.

The fission chamber was located in a port underneath the the reactor.

B. LINEAR P. CONTROL LOOP

The linear P control loop has been in use since the reactor was built. This loop was designed by North American Aviation Company to control power output of the reactor only after the reactor had been manually brought to the desired power level. As pointed out in Ref. 15, it does not operate well when used for a change in power level of the reactor, because in the stabilizing process, the high gain servo amplifier originally caused to saturate in one direction by a manual change in Power Set, goes into saturation in the reverse direction.

The servo amplifier gain varies from less than 10^4 to 2×10^6, depending on the setting of the Power Set. The purpose of this variable gain is to compensate for the different reactor gains at different power levels, and, thereby, provide a constant open loop gain for power levels from 2 W to 2000 Watts. The inverse P shaped gain characteristic of the amplifier was obtained by a combination of switching resistors across which the ionization chamber output voltage was developed, and by the use of a loaded gain compensating potentiometer in the grid circuit of the third stage of the amplifier. Reference 16 discusses this design. In Figure 22, the control loop is shown in block diagram form.

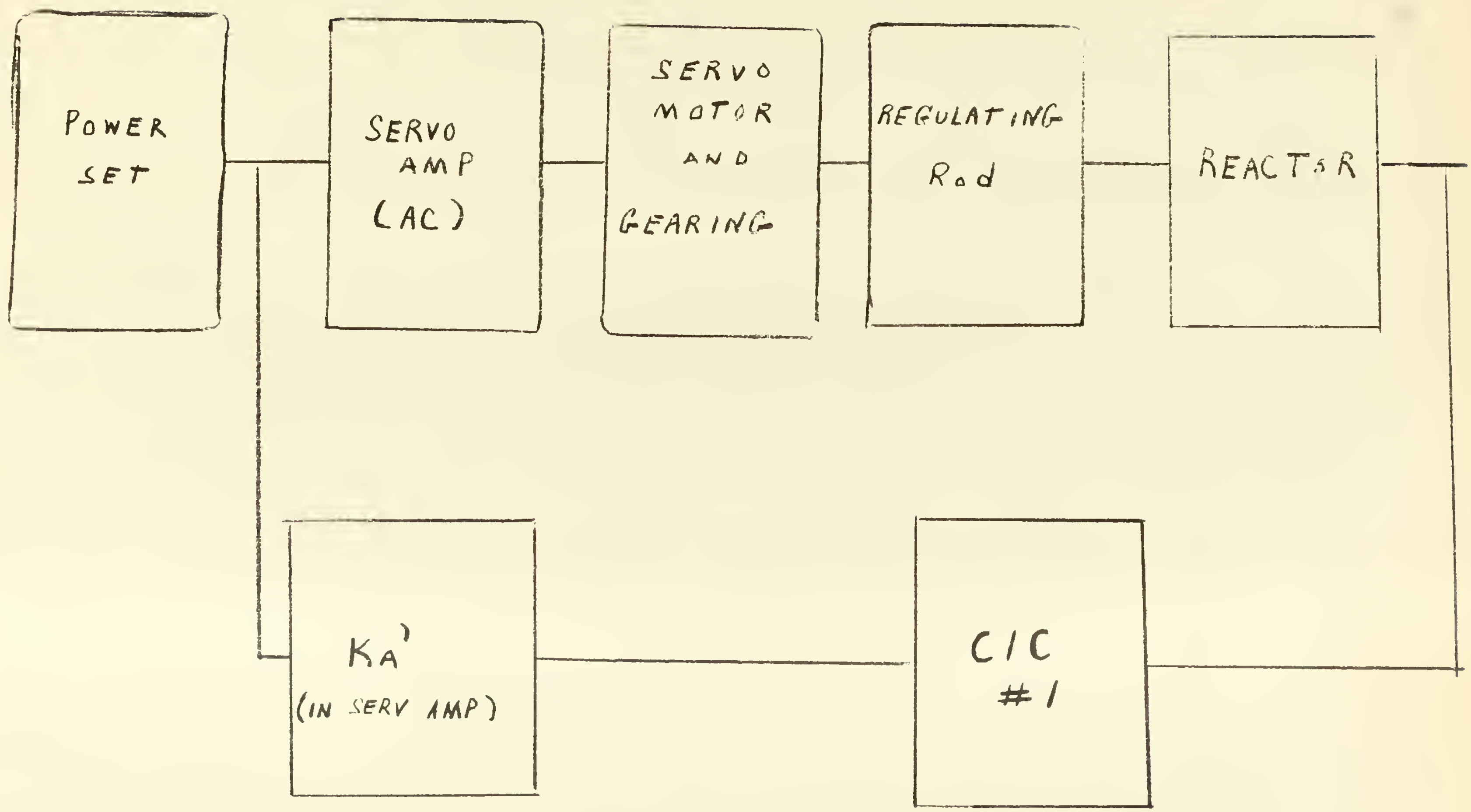

POWER SET
SERVO AMP (AC)
SERVO MOTOR AND GEARING
REGULATING Rod
REACTOR
Ka'
(IN SERV AMP)
CIC #1

FIGURE 22

A linear analysis of this loop based upon transfer functions listed in the section on control units follows:

$$\text{OLTF} = \frac{K_A K_M K_\Lambda K_R K_I K_A' \left(1 + \frac{j\omega}{\omega_a}\right)}{(j\omega)^2 \left(1 + \frac{j\omega}{\omega_A}\right)\left(1 + \frac{j\omega}{\omega_M}\right)\left(1 + \frac{j\omega}{\omega_1}\right)} \tag{52}$$

$$\text{OLTF} = \frac{1.036\times10^{5} \times 2.5\times10^{-3} \times 2.25\times10^{-2} \times 42.3 \times 5\times10^{-8} \times 7.2\times10^{4}\left(1 + \frac{j\omega}{.0829}\right)}{(j\omega)^2\left(1 + \frac{j\omega}{60}\right)\left(1 + \frac{j\omega}{50}\right)\left(1 + \frac{j\omega}{74.3}\right)} \tag{53}$$

$$\text{OLTF} = \frac{0.884\left(1 + \frac{j\omega}{.0829}\right)}{(j\omega)^2\left(1 + \frac{j\omega}{60}\right)\left(1 + \frac{j\omega}{50}\right)\left(1 + \frac{j\omega}{74.3}\right)} \tag{54}$$

$$20 \text{ Log } K = -20 \log 1/.884 = -1.08 \text{ db} \tag{55}$$

The Bode diagram for this open loop transfer function is Figure 23.

From Figure 23

phase margin is 66° at $\omega = 10.5$ rad/sec

gain margin is 16 db at $\omega = 34$ rad/sec

C LOG P CONTROL LOOP

The Log P Control Loop has been synthesized as part of the multi-decade automatic control system. In its design it has been necessary to modify the servo amplifier so that it will exhibit a fixed gain characteristic. (In the initial test design, a slight variation of serv amp gain was allowed). This is necessary because logarithmic characteristic of the Log N Amplifier from CN 4 to CN 12 compensates for increasing reactor power levels with the result that the loop gain is maintained constant.

Figure 24 is a block diagram representation of this control loop.

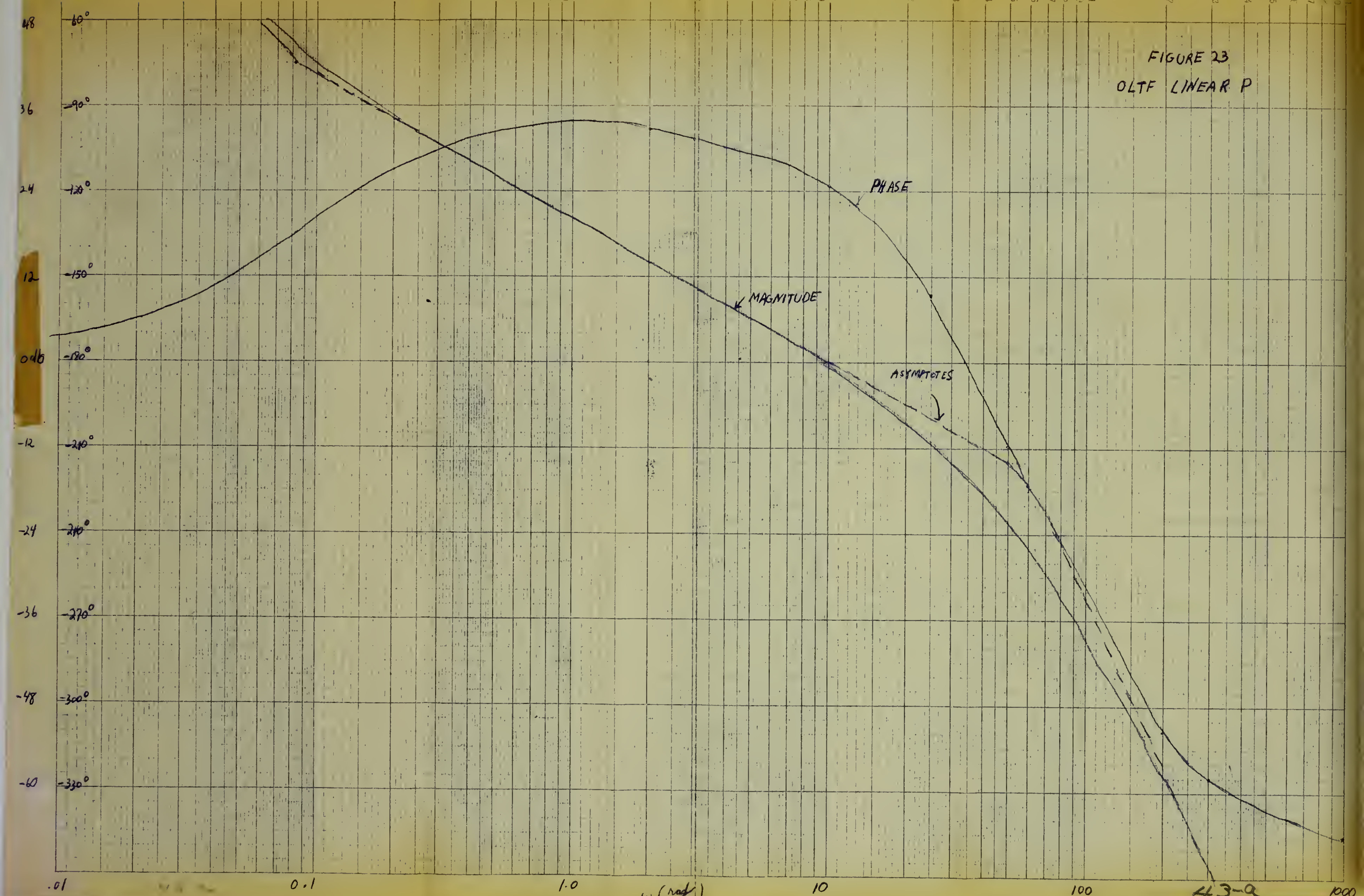


FIGURE 23
OLTF LINEAR P
PHASE
MAGNITUDE
ASYMPTOTES
48
36
24
12
0 db
-12
-24
-36
-48
-60
-60°
-90°
-120°
-150°
-180°
-210°
-240°
-270°
-300°
-330°
.01
0.1
1.0
10
100
1000

43-a

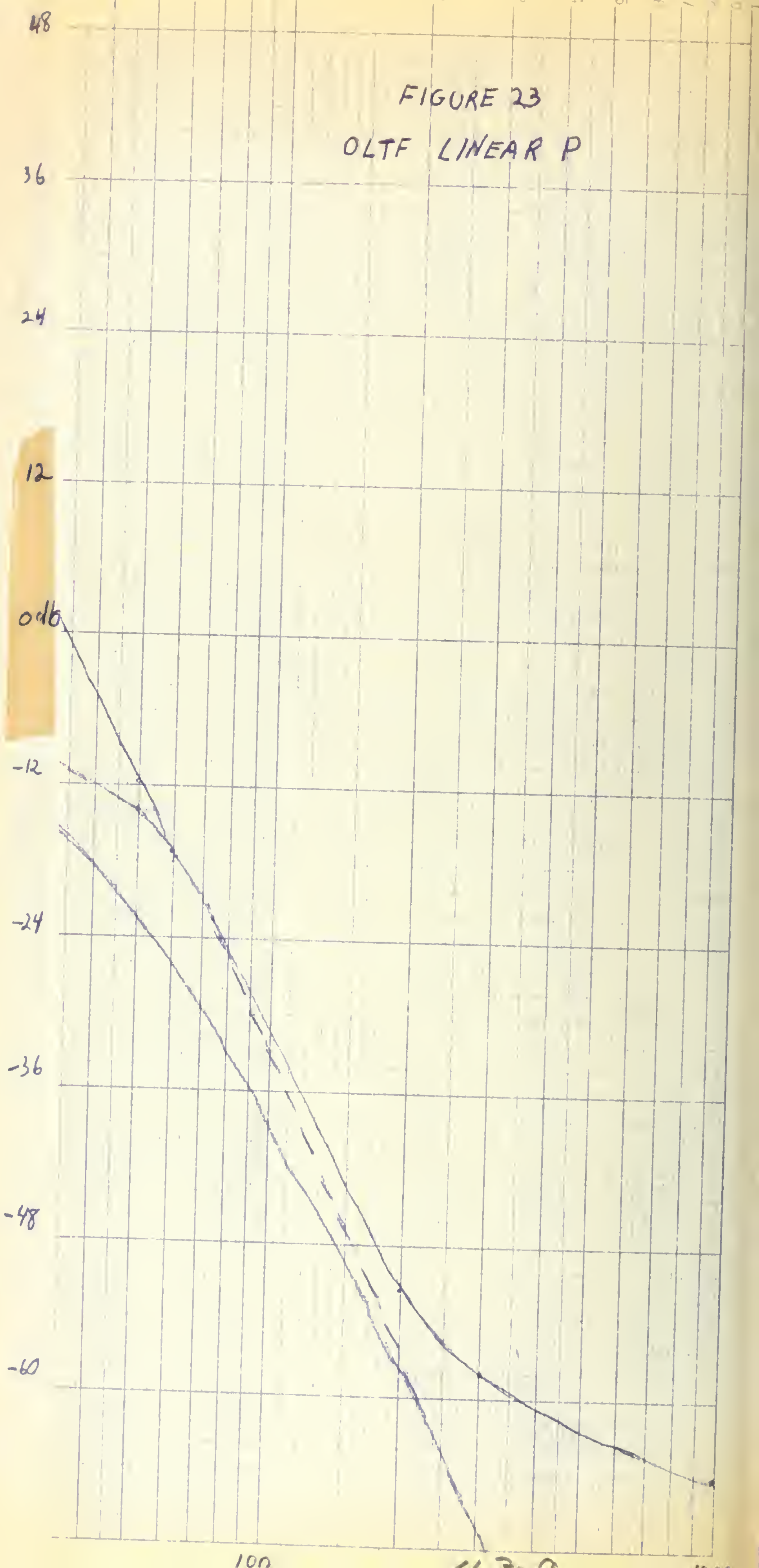


FIGURE 23
OLTF LINEAR P

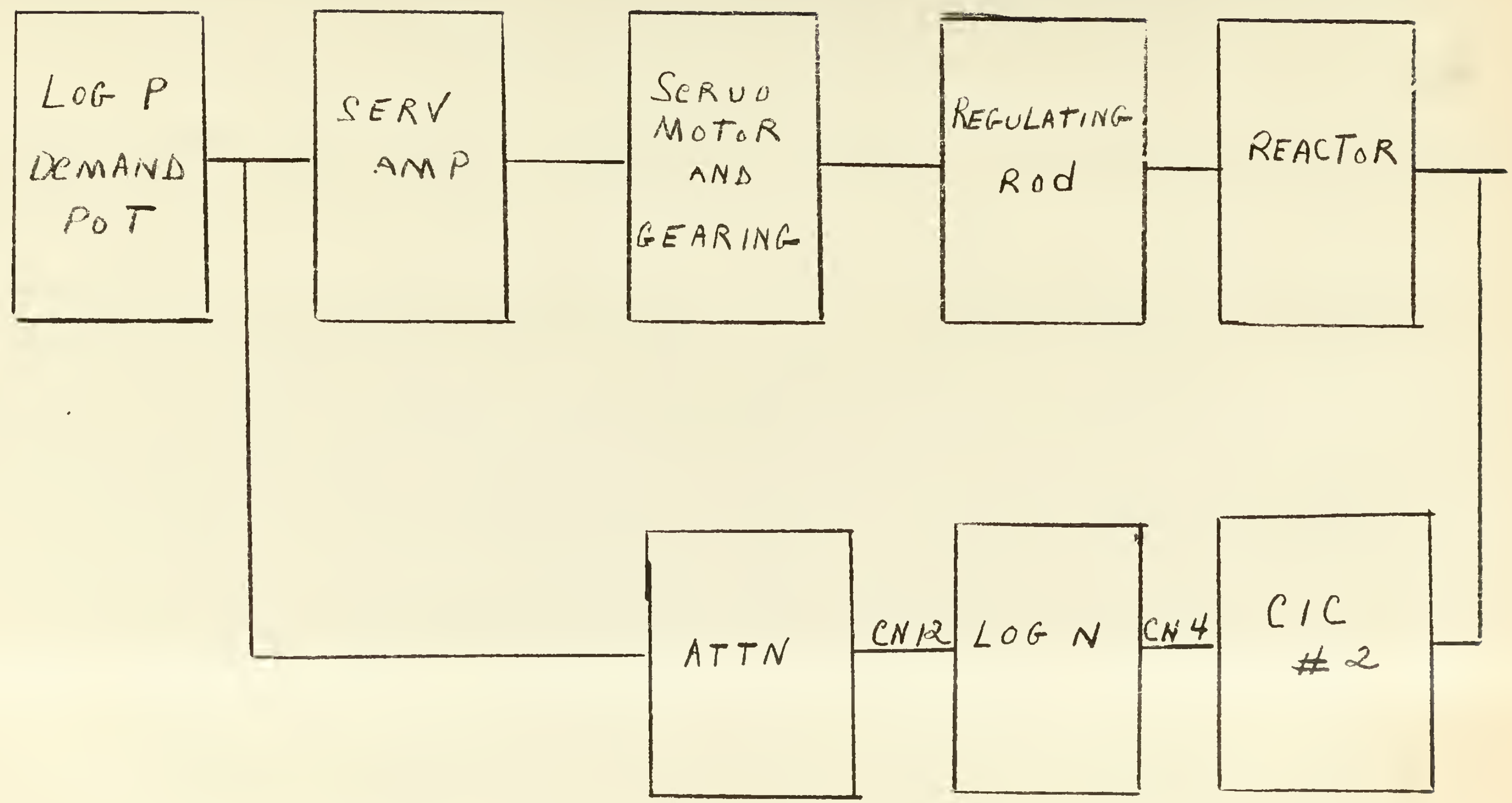

LOG P DEMAND POT
SERV AMP
SERVO MOTOR AND GEARING
REGULATING ROD
REACTOR
ATTN
CN12
LOG N
CN4
CIC #2

FIGURE 24

A linear analysis of this loop based upon transfer functions listed in the section on control units follows:

$$OLTF = \frac{K_A K_M K_A K_R K_I K_N K_{AN} \left(1+\frac{j\omega}{\omega_1}\right)}{(j\omega)^2 \left(1+\frac{j\omega}{\omega_A}\right)\left(1+\frac{j\omega}{\omega_M}\right)\left(1+\frac{j\omega}{\omega_1}\right)\left(1+\frac{j\omega}{\omega_N}\right)} \quad (56)$$

$$OLTF = \frac{2\times10^{6}\times2.5\times10^{-3}\times2.25\times10^{-2}\times 42.3\times5\times10^{-8}\times\frac{1}{32}\times1.63\left(1+\frac{j\omega}{.0829}\right)}{25\times10^{-6}(j\omega)^2\left(1+\frac{j\omega}{60}\right)\left(1+\frac{j\omega}{50}\right)\left(1+\frac{j\omega}{74.3}\right)\left(1+\frac{j\omega}{34.5}\right)} \quad (57)$$

$$OLTF = \frac{4.85\times10^{-2}\left(1+\frac{j\omega}{.0829}\right)}{(j\omega)^2\left(1+\frac{j\omega}{60}\right)\left(1+\frac{j\omega}{50}\right)\left(1+\frac{j\omega}{74.3}\right)\left(1+\frac{j\omega}{34.5}\right)} \quad (58)$$

$$20 \log K = -40 + 20 \log 4.85 = -26.28 \text{ db} \quad (59)$$

From Figure 25

phase margin is 80° at $\omega = 1.1$ rad/sec

gain margin is 28 db at $\omega = 22$ rad/sec

The kinetic characteristics of the loop are adequate, but could be improved by a combination of an increase in gain and phase lead compensation. However, to achieve an increase in gain an additional d-c amplifier would be required.

D INVERSE PERIOD CONTROL LOOP

Like the Log P Control Loop, the Inverse Period Control Loop has been synthesized as part of the multidecade automatic control system. The servo amplifier configuration used with the Log P Control Loop is also used with the Inverse Period Control Loop, although, the compensation afforded by the Period Output of the Log N Amplifier is only approximate as the power

level of the reactor increases.

Figure 26 is a block diagram representation of this control loop.

A linear analysis of this loop based upon transfer functions listed in the section on control units follows:

$$OLTF = \frac{K_A K_M K_n K_R K_I K_{\,} K'_{AN}\left(1+\frac{j\omega}{\omega_a}\right)}{I_J\omega\left(1+\frac{j\omega}{\omega_A}\right)\left(1+\frac{j\omega}{\omega_M}\right)\left(1+\frac{j\omega}{\omega_I}\right)\left(1+\frac{j\omega}{\omega_d}\right)\left(1+\frac{j\omega}{\omega_p}\right)} \qquad (60)$$

Considering performance on a 30 second period.

$$OLTF = \frac{2\times10^{6}\times2.5\times10^{-3}\times2.25\times10^{-2}\times42.3\times10^{-5}\times5\times10^{-8}\times1.5\times10^{-1}\left(1+\frac{j\omega}{.0829}\right)}{25\times10^{-11}j\omega\left(1+\frac{j\omega}{60}\right)\left(1+\frac{j\omega}{50}\right)\left(1+\frac{j\omega}{74.3}\right)\left(1+\frac{j\omega}{1.11}\right)\left(1+\frac{j\omega}{25}\right)} \qquad (61)$$

(The gain computation is performed at 0.05 watts, although, it could have been performed at any power level with the same result.)

(A transfer function term is included for the CIC. This is convenient but not necessary.)

$$OLTF = \frac{144.\times10^{-2}\left(1+\frac{j\omega}{.0829}\right)}{j\omega\left(1+\frac{j\omega}{60}\right)\left(1+\frac{j\omega}{50}\right)\left(1+\frac{j\omega}{74.3}\right)\left(1+\frac{j\omega}{1.11}\right)\left(1+\frac{j\omega}{25}\right)} \qquad (62)$$

$$20 \log K = 20 \log 1.44 = 3.16 \text{ db} \qquad (63)$$

The Bode diagram for this open loop transfer function is Figure 27.

An inspection of Figure 27 indicates stability is only a little better than marginal in this loop. However, the analog computer study brought out the fact that the loop is stable even with higher gain in the composite period detector.

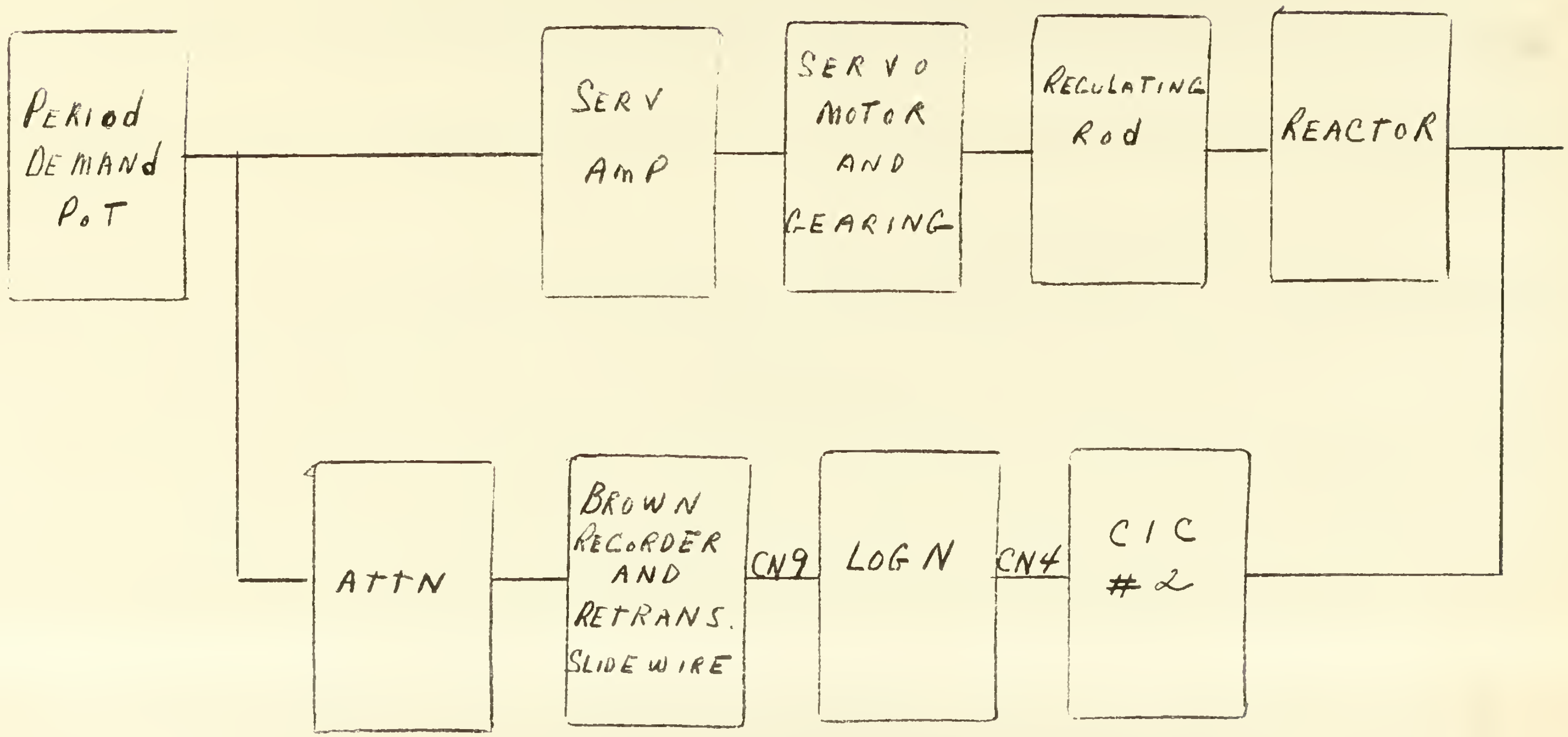

PERIOD DEMAND POT
SERV AMP
SERVO MOTOR AND GEARING
REGULATING ROD
REACTOR
ATTN
BROWN RECORDER AND RETRANS. SLIDEWIRE
CN9
LOG N
CN4
CIC #2

FIGURE 26

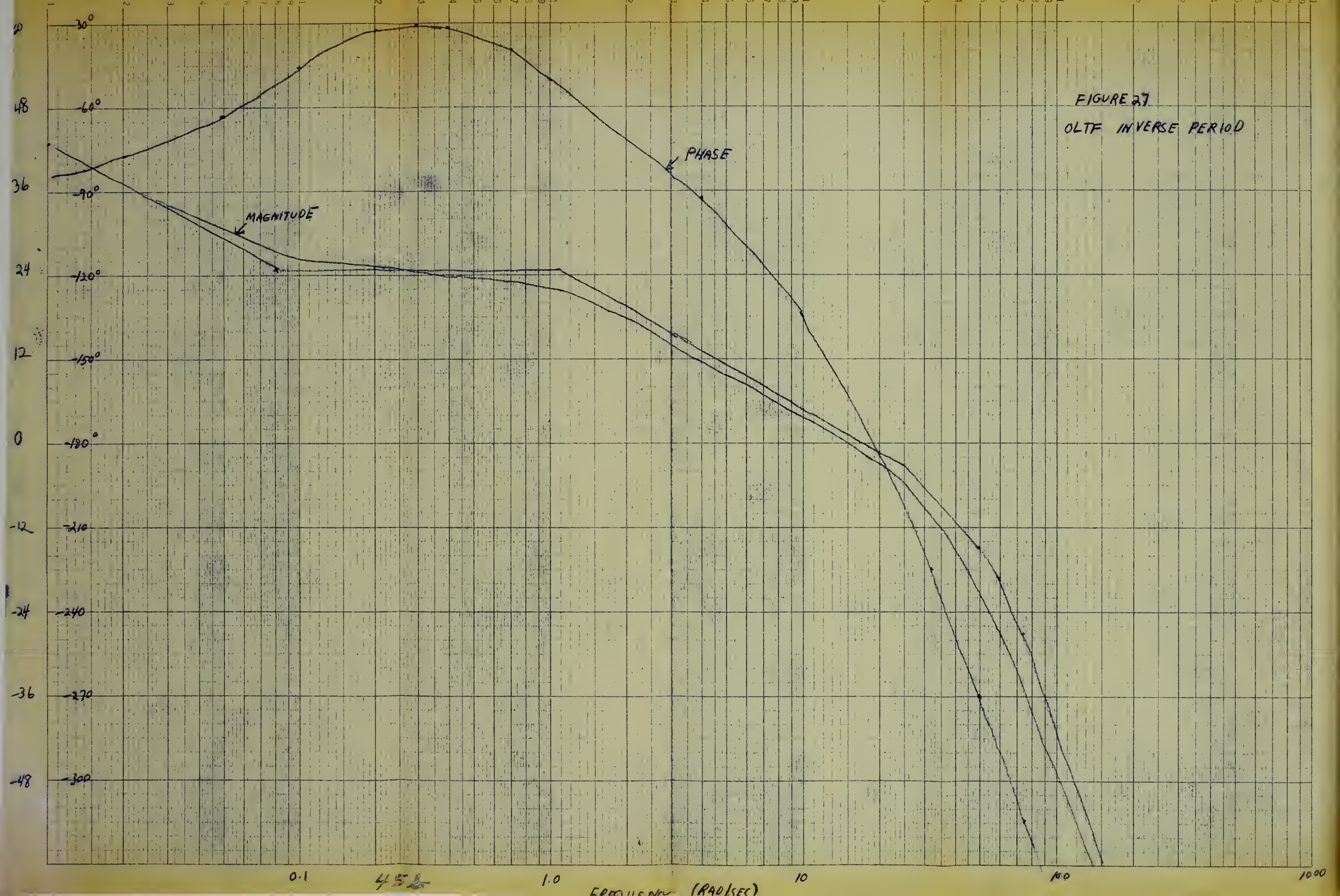


FIGURE 27
OLTF INVERSE PERIOD
PHASE
MAGNITUDE
-30°
-60°
-90°
-120°
-150°
-180°
-210
-240
-270
-300
48
36
24
12
0
-12
-24
-36
-48
0.1
1.0
10
100
1000
FREQUENCY (RAD/SEC)

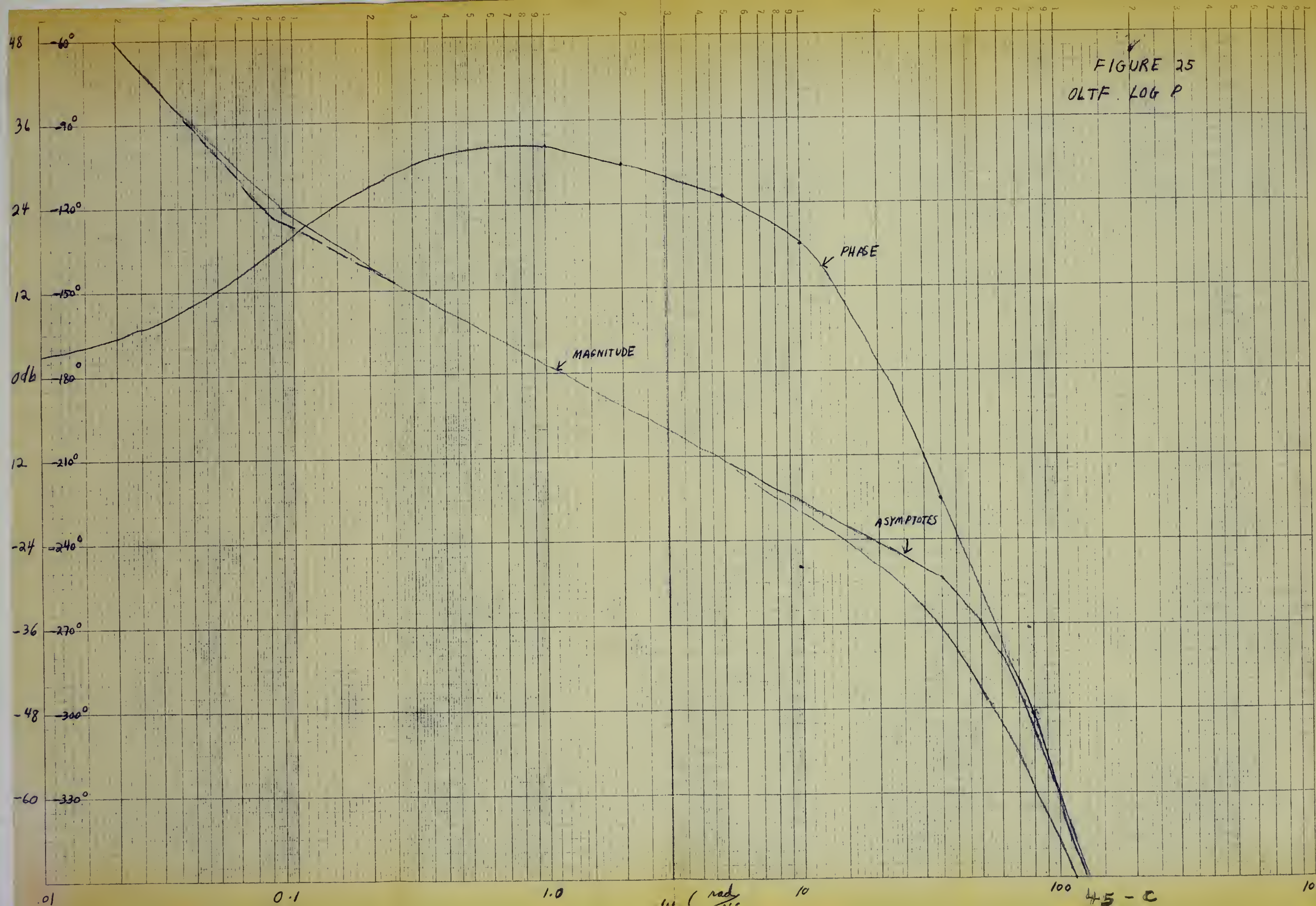


FIGURE 25
OLTF LOG P
PHASE
MAGNITUDE
ASYMPTOTES
48
36
24
12
0db
12
-24
-36
-48
-60
-60°
-90°
-120°
-150°
-180°
-210°
-240°
-270°
-300°
-330°
.01
0.1
1.0
10
100
1000

Fortunately, excess gain is readily available in this loop and the loop gain may be readily adjusted to optimum. In operation of the circuit with the reactor, operation at marginal stability was obtained with 0.4 volts corresponding to a 30 second period. However, the OLTF with this new gain constant is not precisely known because of the deviation of servo amplifier gain from the theoretical value and because of non-linear operation.

MECHANICAL DESIGN OF THE CONTROL SYSTEM

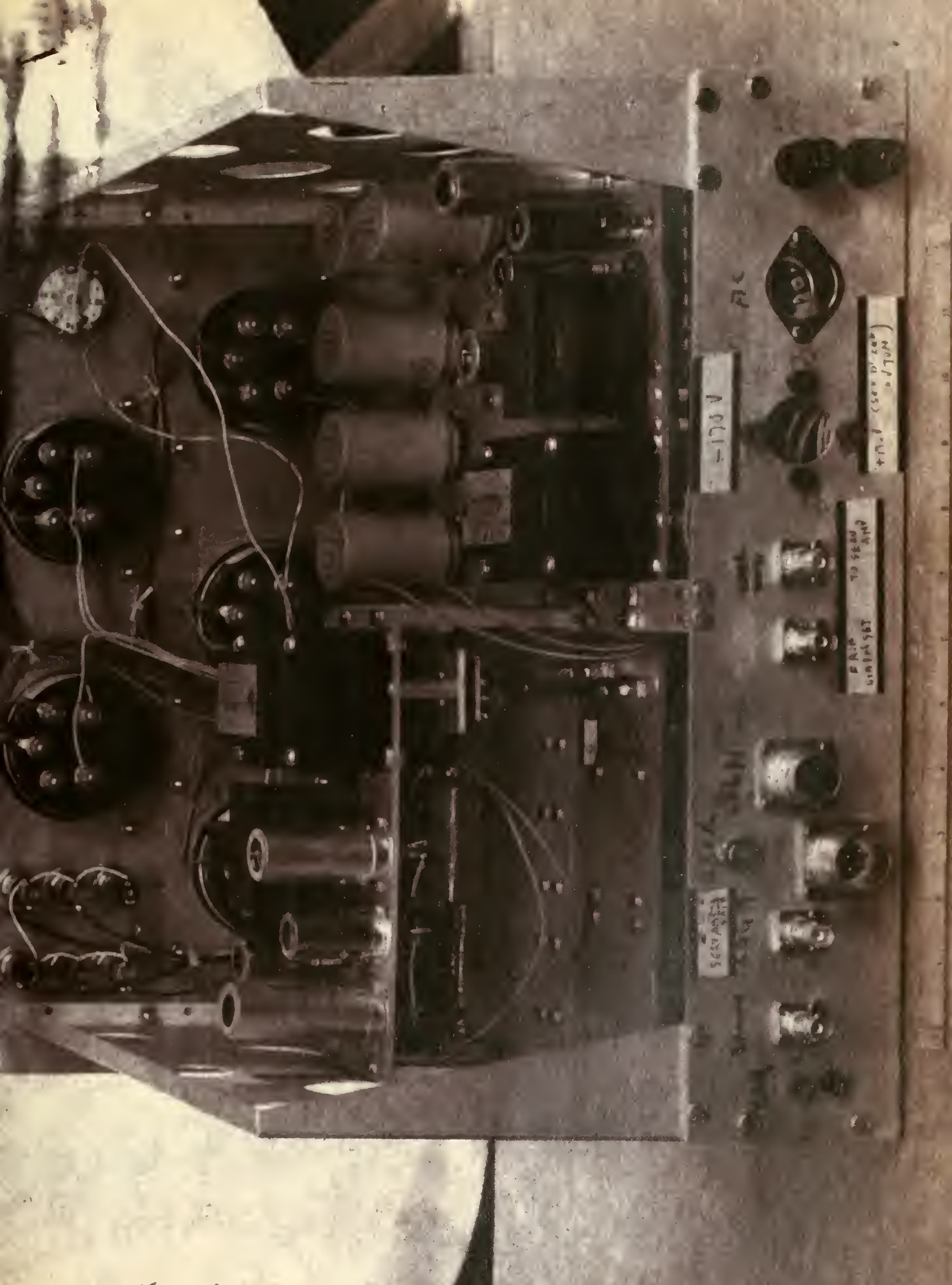
A - CONTROL CHASSIS:

A requirement was imposed on the size of the front panel by the available mounting space in the control console. Panel #1 (Ref 13) of the console was not already in use and provided an adequate location from which the status lights on the chassis would be visible to the operator. Because of grounding considerations, it is also desirable that the front panel be insulated from the remainder of the control chassis.

Figures 28, 29, and 30 show views of the control chassis. There is an error in Figure 29. Potentiometer labelled serv amp gain 250K should read Period Run-Up 100 K.

Human engineering aspects were considered. The array of meters at first seems confusing, however, they do provide a ready indication of the status of the startup operation. The meter readings of themselves are not significant, however, the dial divisions provide convenient calibration points.

FIGURE 28 (COURTESY LAWRENCE RADIATION LABORATORY)



46 b

FIGURE 29 (COURTESY LAWRENCE RADIATION LABORATORY)

46 c

FIGURE 30

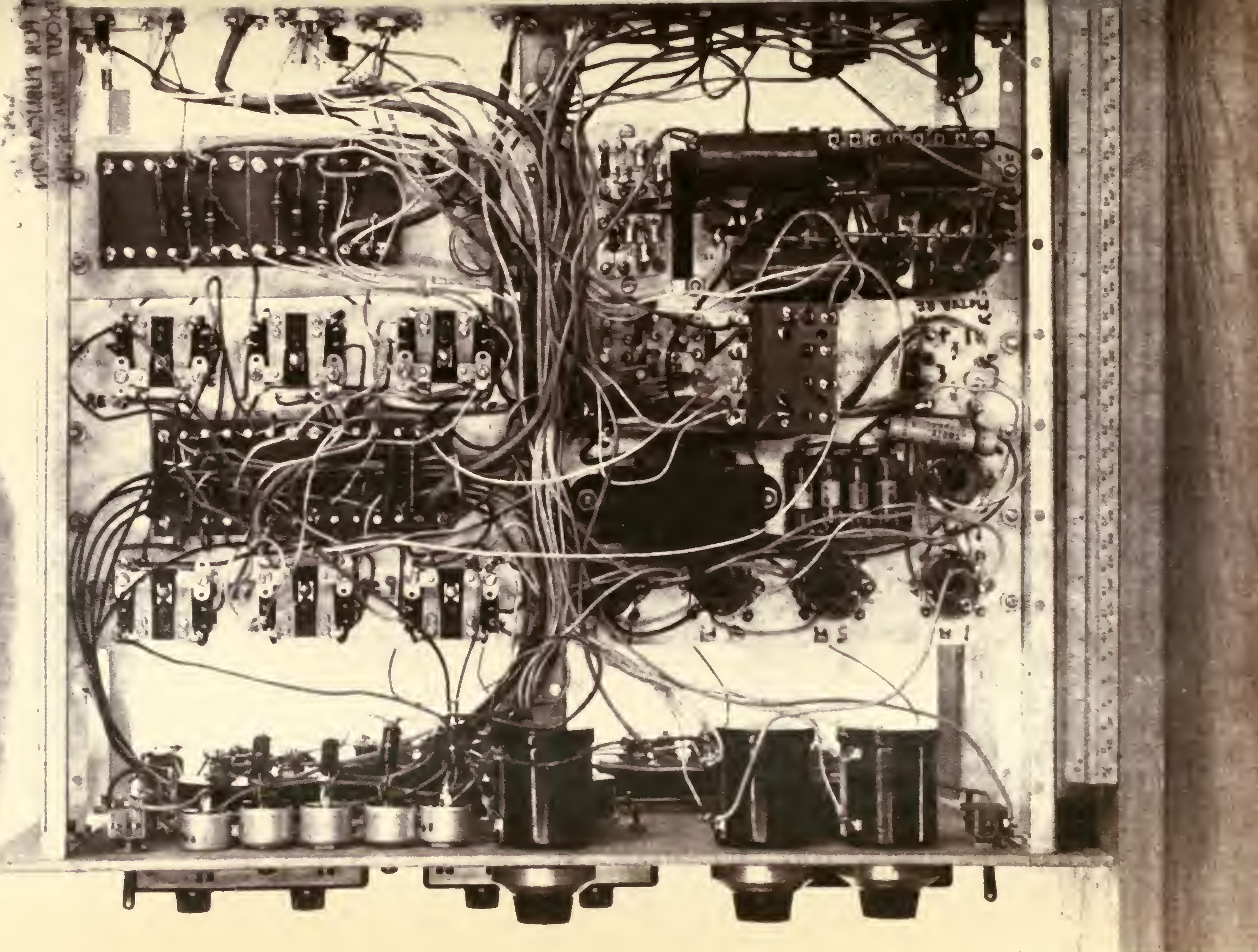


FIGURE 30 (Courtesy Lawrence Radiation LAB)

What is important is that a lance at the meters and the relative position of the meter movement arm and limit contacts will tell the operator the status of the startup operation, and give indications as to whether or not the control chassis is functioning properly. The status lights give the operator a fast indication of the status of the control sequence during startup. These lights operate sequentially and can be a red-yellow-green sequence to indicate progress of the startup.

Reset buttons are provided for reprogramming a new startup. Helipots allow accurate setting of necessary imput quantities. A three position switch is provided to select control mode sequence.

Various types of connectors are used at the rear of the chassis where all external connections to the control chassis are made.

Convenient points for checking power supply reference voltages are provided on the rear of the chassis.

This original chassis was constructed primarily as an experimental device and, therefore, greater flexibility was built into the operating controls than would otherwise be required.

B - OTHER SYSTEM COMPONENTS:

The CRM was mounted beneath the scaler presently installed in the control console (lower right hand panel). (Ref 13) The linear amplifier, blocking oscillator and fission chamber preamplifier were located in a rack near the reactor stringer doors.

The Period Channel Brown Amplifier was mounted on top of the control console. By using the available recorder mechanism, the period indication can be displayed more accurately than the Log N period meter reading because of the expanded scale of the period recorder.

ANALOG SIMULATION

Berkeley 1031 and 1032 analog computers were used in the design process for the purposes of checking loop gain, control mode switching, and for debugging the hardware developed prior to using it to control the waterboiler. The programming and setting up of the computers was done by Mr. Stanley Ross of UCRL. A discussion and interpretation of the results follows:

The setup used for evaluating and debugging the hardware included both the 1032 and 1031 analog computers because of the large number of operational amplifiers required. A 6 channel recorder was used to show graphically the behavior of problem variables. The new control chassis was used as an integral part of the simulated system.

Figure 31 shows a typical startup sequence indicated at the bottom of the Figure as ID - Per - Lin P (40 sec per) to show that the sequence of events was initial rod drive followed by period loop control (where the demanded period was 40 seconds) followed by Linear P Loop Control. Because of computer limitations the startup range was compressed to the region 5 watts to 500 watts. As shown on the Figure, Pen #1

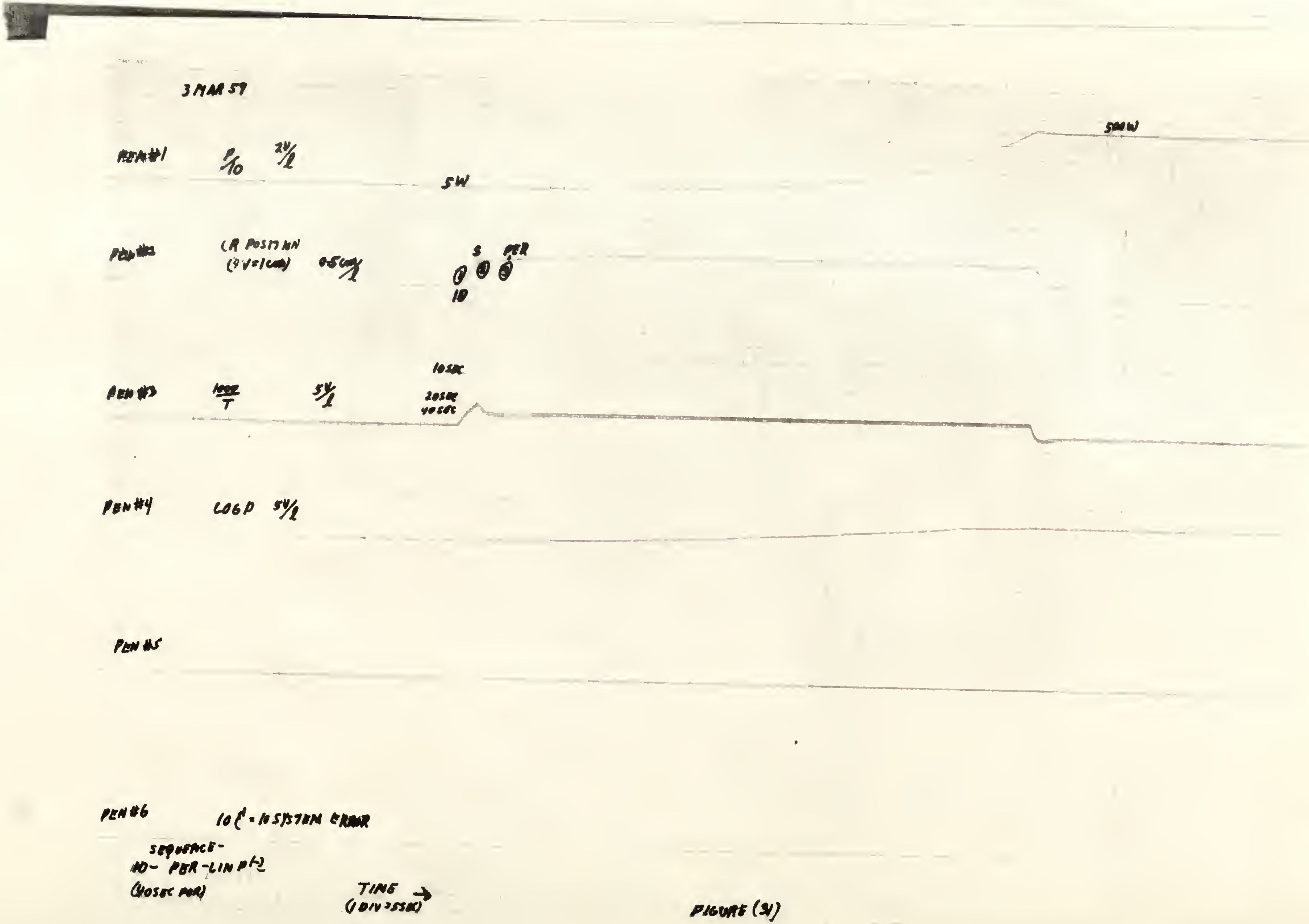

3 MAR 59
PEN #1
P/10
2V/2
5W
500W
PEN #2
CR POSITION
(9V=1CM)
0.5CM/2
S
PER
10
PEN #3
100R/T
5V/2
10SEC
20SEC
40SEC
PEN #4
LOG P
5V/2
PEN #5
PEN #6
10 C = 10 SYSTEM ERROR
SEQUENCE-
NO- PER-LIN P(-2)
(40SEC PER)
TIME →
(1 DIV = 5SEC)

FIGURE (31)

records P/10(1/10 reactor power level) Pen #2, CR Position (control rod position) Pen #3 records 1000/T (1000/Period), Pen #4 Log P, Pen #5 (not used) Pen #6 10 E (10 System Error). At time 1 (refer Pen 2 trace) the automatic control system was turned on. This is a simulated start from source level. At time 2, the initial rod drive was stopped (manually by the computer operator since this switching could not be simulated by the computer.) At time 3, the system was placed in period control by the computer operator (this switching could not be simulated by the computer). Even though the computer operator had to serve as part of the control loop, nevertheless, this evaluation was quite useful as a check of the operation of the control chassis in response to these signals.

Once the system had been placed in period control, then the rest of the simulation was done by the computer exclusively.

Figure 32 shows a similar sequence but with Log P control substituted for Lin P control, with the switching from Per to Log P after the Log P error reversed sign. Figure 33 shows a sequence wherein the switching from Per to Log P occurs before the Log P error reversed sign. Note that in this case at time 4 the motion of the control rod is first out then in, with a corresponding decrease in period, followed by the increased period.

In Figure 34 is shown the effect of demanding a relatively fast period (15 sec.). It should be noted that, because of the feature whereby control is switched from Per to Lin P after the Lin P error signal reverses sign, there

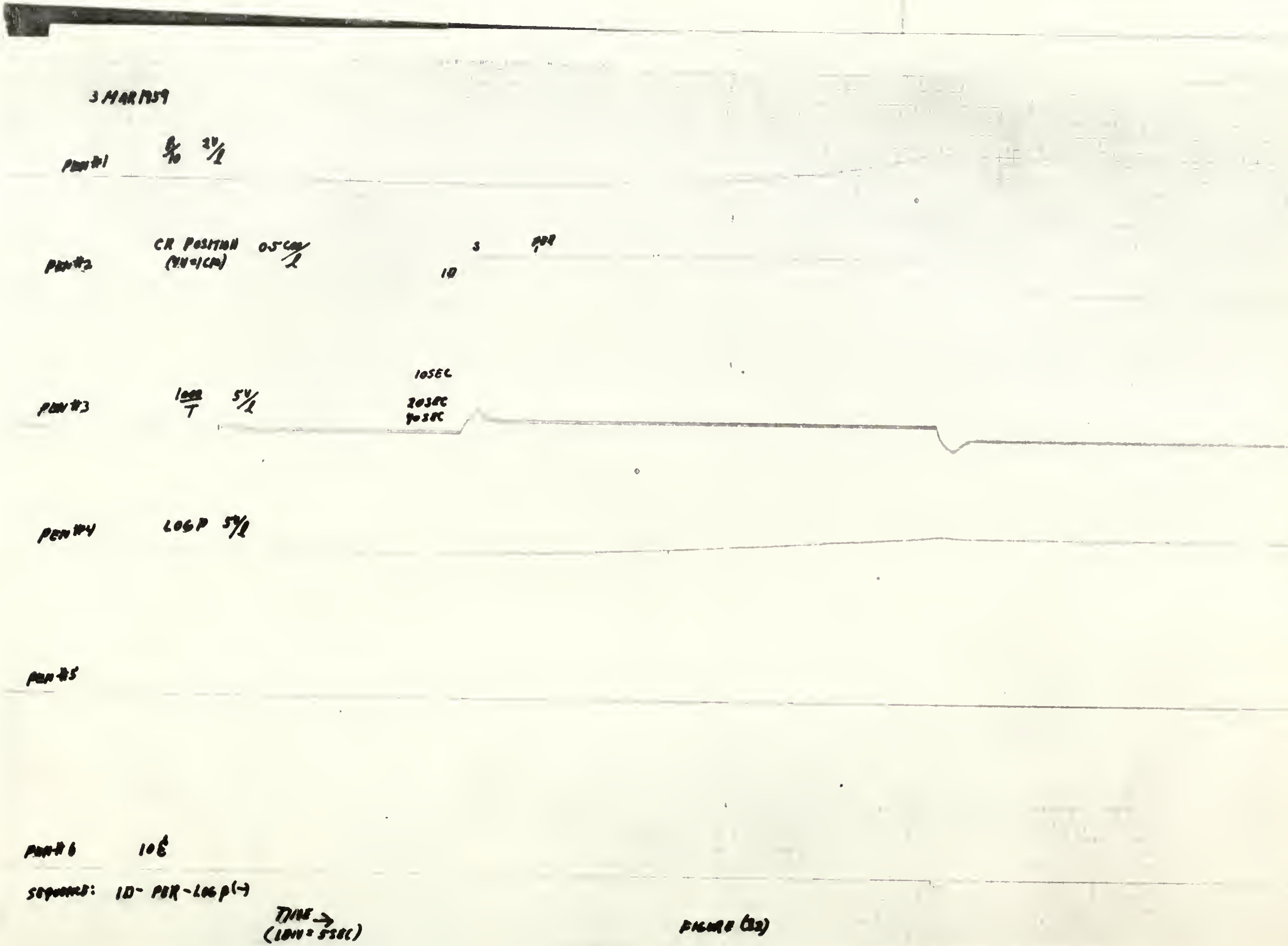

3 MAR 1959
PEN #1 8/10 2V/1
PEN #2 CR POSITION (1DIV=1CM) 0.5CM/1
10
5
PPR
PEN #3 1000/T 5V/1
10SEC
20SEC
40SEC
PEN #4 LOG P 5V/1
PEN #5
PEN #6 10E
SEQUENCE: 1D- PER-LOG P(-)
TIME →
(1DIV=5SEC)

FIGURE (32)

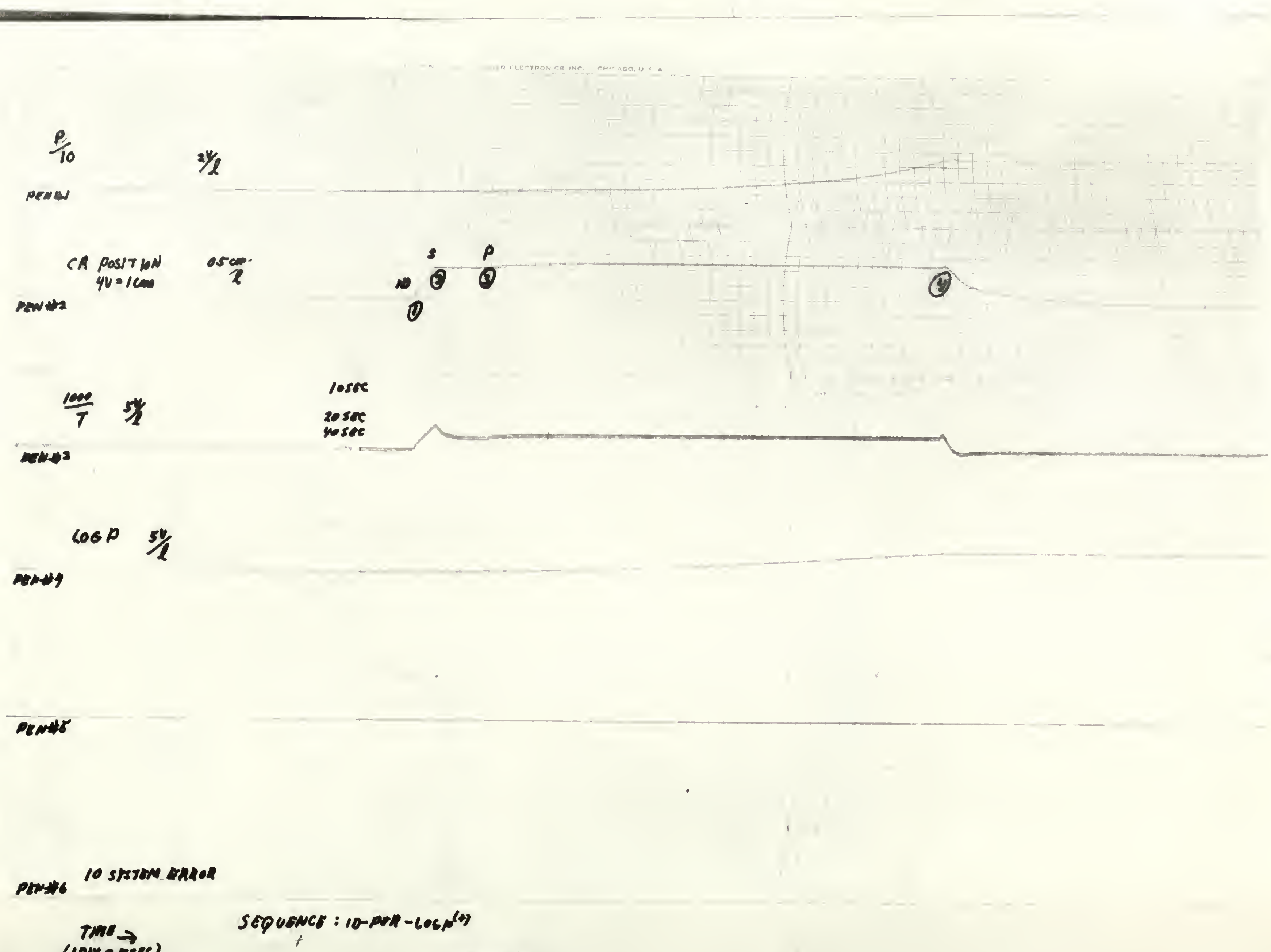
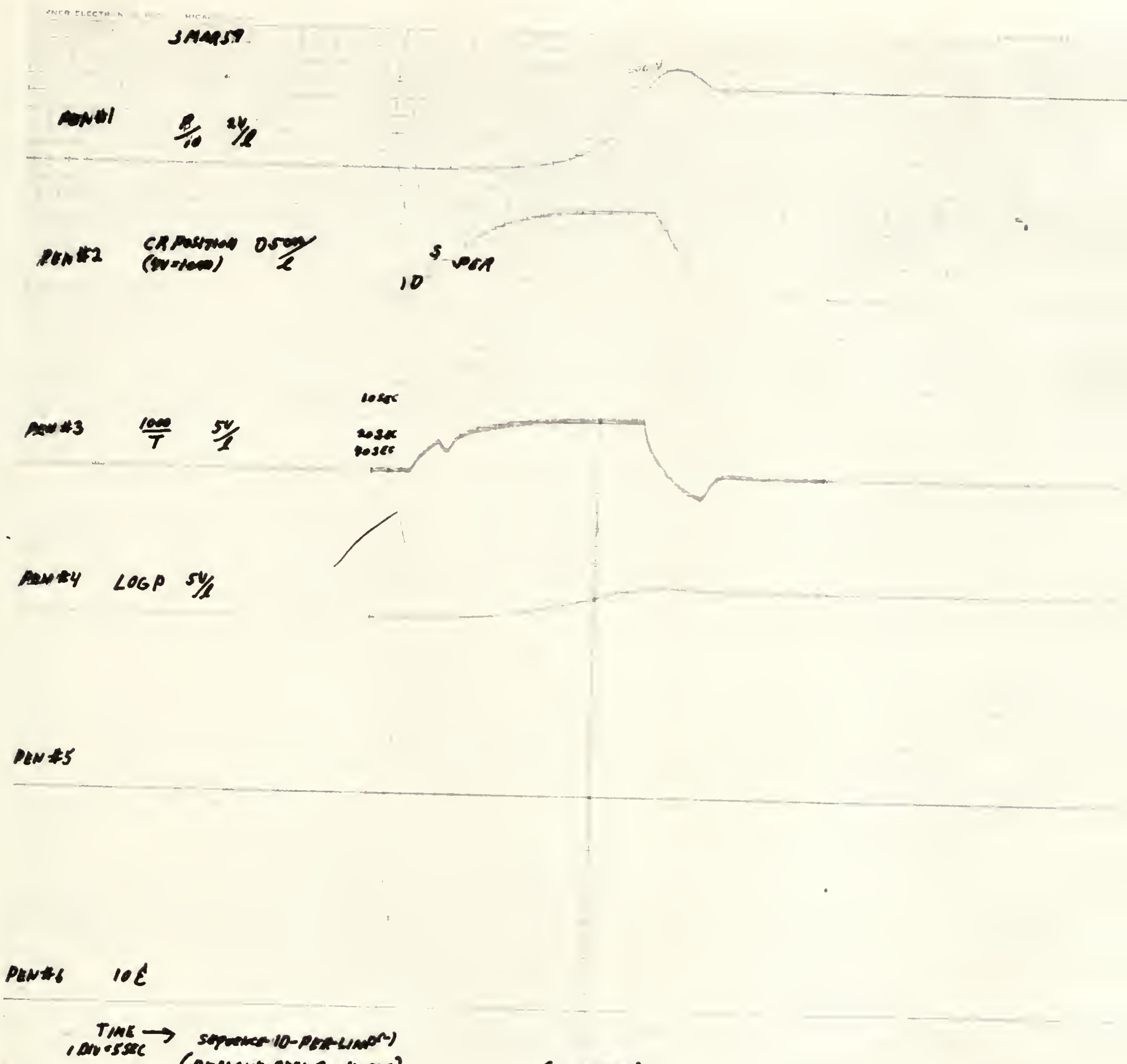

P/10 2V/2
PEN#1
CR POSITION 4V=1CM
.05CM/2
PEN#2
10
S
P
1000/T 5V/2
10SEC
20SEC
40SEC
PEN#3
LOG P 5V/2
PEN#4
PEN#5
PEN#6 10 SYSTEM ERROR
TIME → (1DIV=5SEC)
SEQUENCE : 10-PCR-LOG P(+)

FIGURE (33)


3MAR59
PEN#1
PEN#2 CR POSITION (9V=1000) 0.5V/L
10 S PER
10 SEC
20 SEC
40 SEC
PEN#3 1000/T 5V/L
PEN#4 LOG P 5V/L
PEN#5
PEN#6 10E
TIME → 1 DIV=5SEC
SEQUENCE 10-PER-LIMIT
(DEMAND PERIOD 14 SEC)

(FIGURE 39)

is no overshoot in period at this switchpoint no matter how fast a period is demanded. The overshoot in power (20%), while safe, is, nevertheless, excessive. Moreover, the amount of overshoot has been shown to be sensitive to the setting of the switch point. This defect has been largely overcome by incorporating a Period Run-Up feature discussed elsewhere in this paper.

In Figure 35 is shown a programmed reduction in power level using the Lin-Log control mode.

Figure 36 illustrates a fail-safe feature of the control chassis. At time 4 the 115 V AC supplying the control chassis was turned off in order to simulate an accidental loss of a-c power. Immediately, a large error signal of the correct polarity and magnitude to cause complete insertion of the fine rod at maximum speed was introduced into the control loop. By design this will occur regardless of which control loop happened to be controlling the reactor at the time of a loss of AC power.

TEST OF CONTROL SYSTEM WITH THE WATERBOILER:

Prior to allowing the control system to operate the water boiler, test runs were made with an operator running the reactor, but with parts of the control system in operation. The first tests involved a checkout of the CRM initial rod drive stop channel. After operation of this channel was satisfactory, the control unit was connected in and the operator again ran the reactor, during which time the control

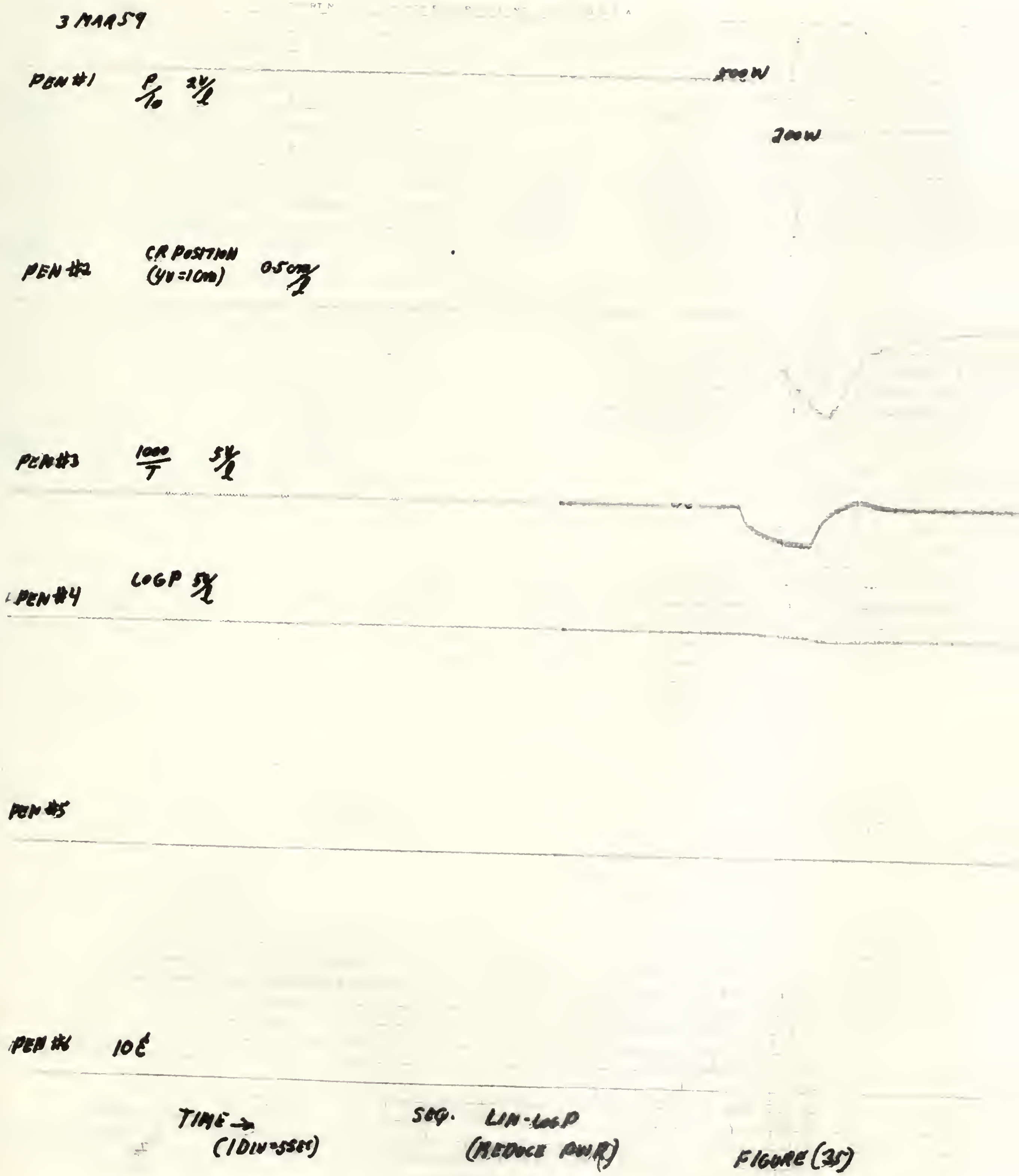
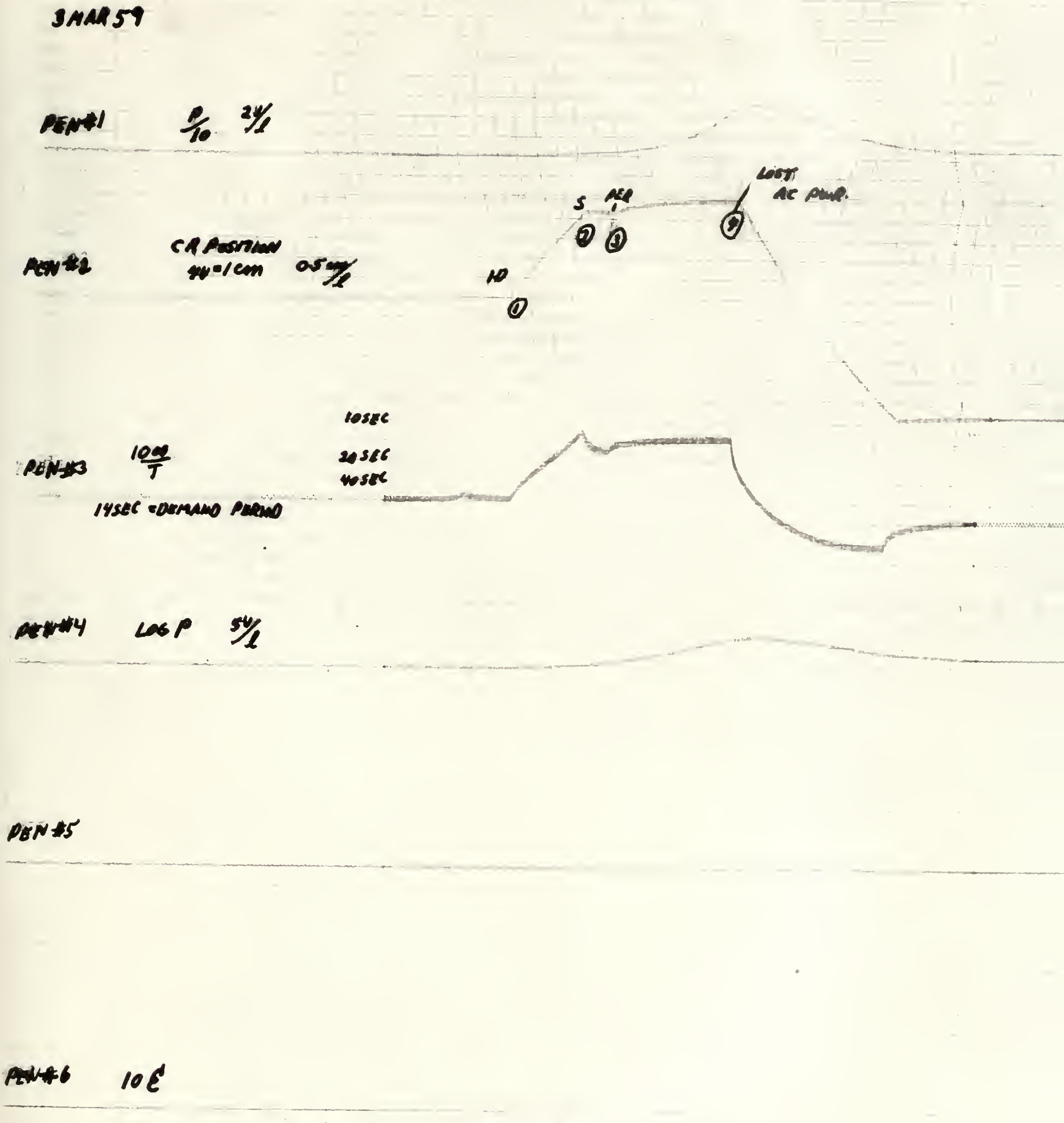

3 MAR59
PEN#1 P/10 2V/L
500W
200W
PEN#2 CR POSITION (4V=1CM) 0.5CM/L
PEN#3 1000/T 5V/L
PEN#4 LOGP 5V/L
PEN#5
PEN#6 10E
TIME →
(1DIV=5SEC)
SEQ. LIN-LOGP
(REDUCE PWR)

FIGURE (35)



ACCIDENT SIMULATION (LOSS OF AC PWR TO CONTROL CHASSIS) FIGURE (36)

system was observed and initial adjustments of the relay switch points were made. After this sequence of tests was completed, various tests of the control system were performed with the control system actually starting the reactor from effectively below the counter range and bringing the reactor to full power.

The various experiments performed using the Automatic Control System included:

1. Startup from near source level at a programmed rod rate.

2. Period control over $4\frac{1}{2}$ decades using various demanded periods in the range, 400 seconds to 10 seconds.

3. Log power control at various levels in the range 0.04 watts to 500 watts.

4. Multimode operation

   a. Fixed error to period error to linear P

   b. Fixed error to period to log P.

   c. Lin P to Log P.

   d. Period to Linear P.

   e. Period to Log P.

5. By means of an oscillator rod, a sinusoidal disturbance in reactivity was introduced and the effectiveness of the control system in Log P control demonstrated.

6. Use of the coarse rod as a negative reactivity booster was investigated.

7. An inverse period run-up feature was evaluated.

A NOISE PROBLEM

Some of the problems encountered included circuit noise in the control chassis. Because of the high gain of the servo amplifier, any noise was greatly amplified and caused distortion of the servo amplifier output waveform. To reduce the 60 cycle hum present, a low pass filter was added in series with the input to the servo amplifier. In an improved design of the control chassis, much of this hum can be eliminated by more effective shielding of the si nal circuitry and possibly the noise filter will no longer be necessary. Any hum of peak amplitude greater than 0.1 millivolts saturates the amplifier when actual amplifier gain equals theoretical gain.

If the 3 db frequency of the filter is about 100 rad/sec it will not have any significant effect upon the stability of the various control loops, however, it will effectively attenuate 60 cps (377 rad/sec).

If $T = \frac{1}{\omega_0} = \frac{1}{100} = .01$ sec

C Choose R small, $R = 5K$

$$C = \frac{T}{R} = \frac{10 \times 10^{-3}}{5 \times 10^{+3}} = 2 \mu f \text{ (non electrolytic)}$$

This filter was effective in reducing the hum to a value at which successful operation of the control system was possible. It is shown schematically in Figure 18.

B - AUTOMATIC STARTUP FROM NEAR SOURCE LEVEL TO FULL POWER

Figure 37 is a crude attempt to show an automatic startup record. During the startup shown, the recorder was initially

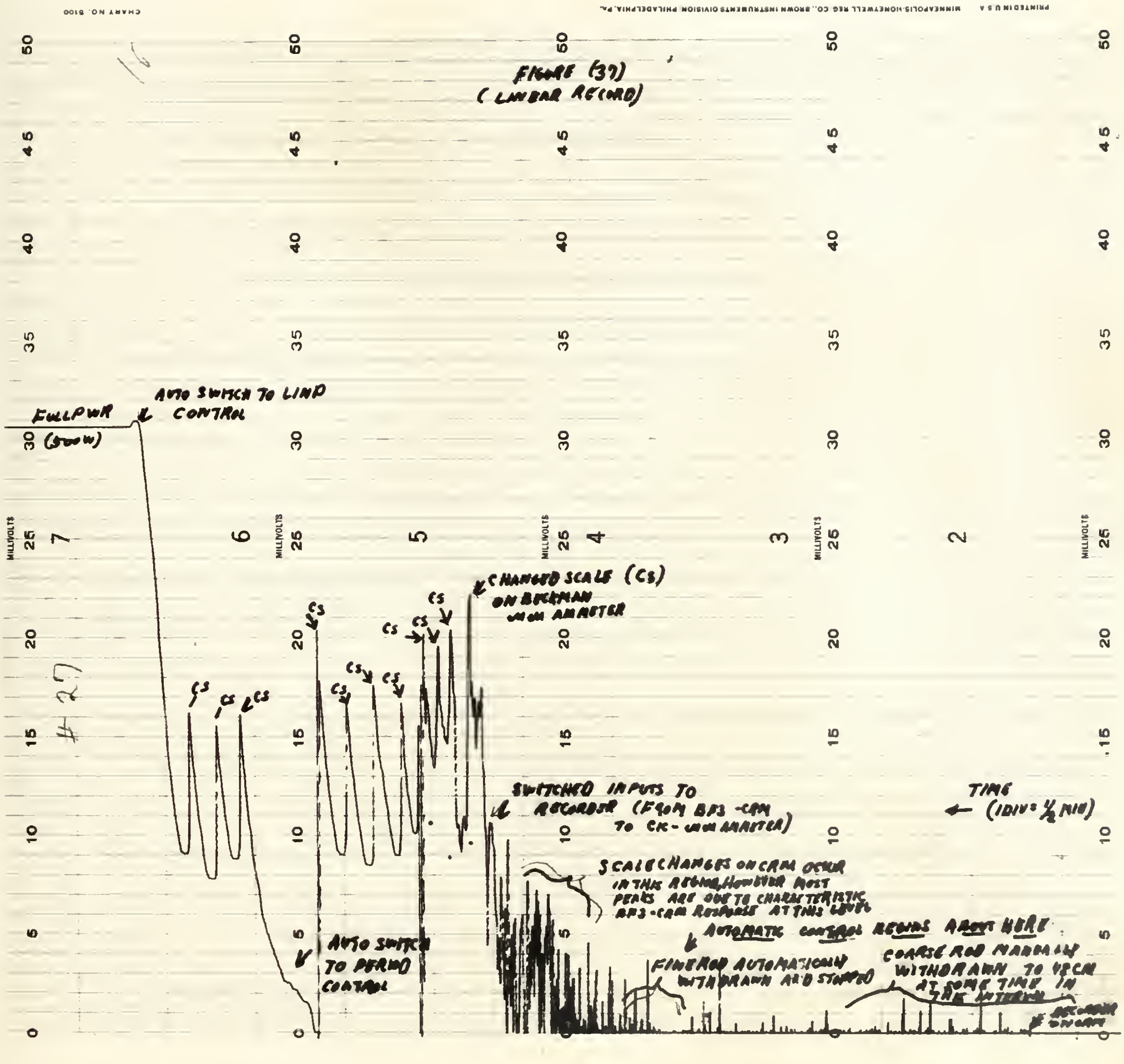


FIGURE (37)
(LINEAR RECORD)
FULL PWR
(500W)
AUTO SWITCH TO LIND CONTROL
CS
CHANGED SCALE (CS) ON BECKMAN MM AMMETER
SWITCHED INPUTS TO RECORDER (FROM BF3 -CAM TO CK-MM AMMETER)
TIME (1DIV= 1/2 MIN)
SCALE CHANGES ON CAM OCCUR IN THIS REGION, HOWEVER MOST PEAKS ARE DUE TO CHARACTERISTIC BF3-CAM RESPONSE AT THIS LEVEL
AUTOMATIC CONTROL BEGINS ABOUT HERE
AUTO SWITCH TO PERIOD CONTROL
FINE ROD AUTOMATICALLY WITHDRAWN AND STOPPED
COARSE ROD MANUALLY WITHDRAWN TO 48CM AT SOME TIME IN THE INTERVAL
MILLIVOLTS
#27

connected to a CRM - BF3 channel and, finally, to a Beckman micromicroammeter - CIC Channel. Neither of these channels was used in the control loops controlling the motion of the fine rod. The information available from the fission chamber-CRM channel which was used to stop the motion of the fine rod initially was not as erratic as the recorded output of the CRM-BF3 channel. One reason is that the fission chamber is less susceptible to gamma counting than is the BF3. While it may seem that automatic control is being used based upon information which has poor statistics, it must be realized that the human operator essentially has no more information available, and uses a procedure similar to that used by the electronic circuits. The human operator may withdraw the rod in steps to determine when the reactor is critical. The automatic operator, by virtue of the much greater speed and precision with which an electronic circuit can make decisions, can be programmed (that is be given experience) to use available data sooner in order to decide when to stop the rod.

The design criterion, then, is restriction of the rate of initial withdrawal of the fine rod to those speeds which allow sufficient information to be available to the automatic operator to make the proper decision as to when to stop the fine rod to put the reactor on a safe period.

Experimentally, it was determined that the automatic operator was capable of consistently stopping the fine rod so as to produce a safe rate of rise of reactor power level and this capability included automatic compensation for

different core temperatures at startup.

While it is realized that this feature is not essential to proper startup of the water boiler, nevertheless, it is felt that demonstration of the principle is of value for those future nuclear reactor applications wherein remote control of the reactor over all power levels would be desirable.

C PERFORMANCE NEAR FULL POWER

Power overshoot can be made negligible and still a relatively fast period can be used over most of the $4\frac{1}{2}$ decade period range as is indicated by the experimental results shown in Figures 38, 39, and 40.

Figure 38 is a logarithmic record of the final stages of an automatic startup with a demanded 30 second period and a demanded 500 watt power level. This record was obtained from a recorder which received an input from CN 11 of the log N amplifier.

Figure 39 is a linear record of the final stages of the same automatic startup. As in Figure 31, the peaks are caused when the operator switches scales on the linear Beckman micro-microammeter which furnishes the input to the recorder from which this record was taken.

Figure 40 is a linear record of an automatic restart using a 30 second demanded period and power demand of 500 watts.

D - FAST PERIOD RUN

Figure 41 is a logarithmic rocord of the final stages of an automatic startup with a demanded 10 second period and a demanded 500 watt power level. Only one run was made with

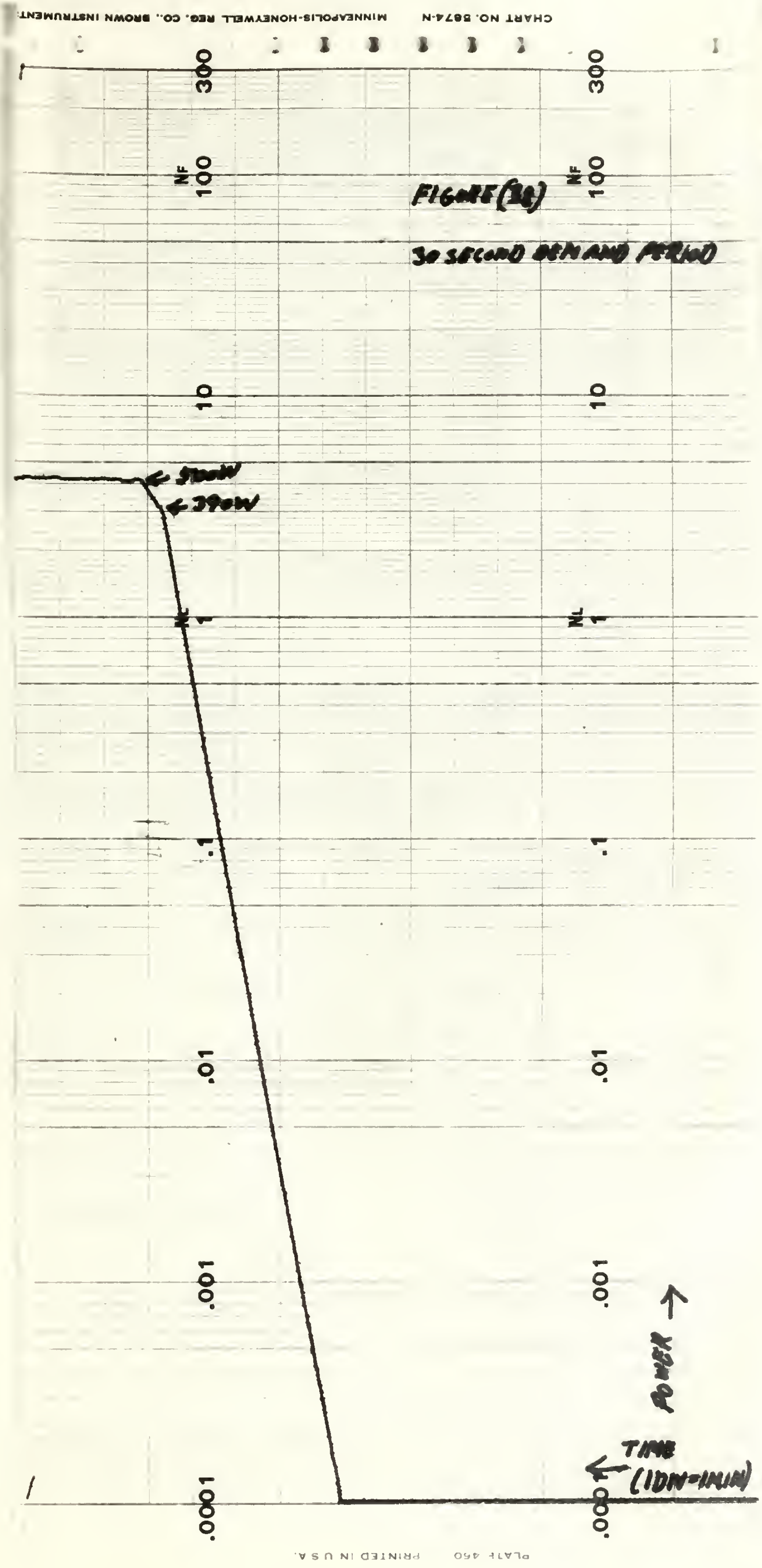
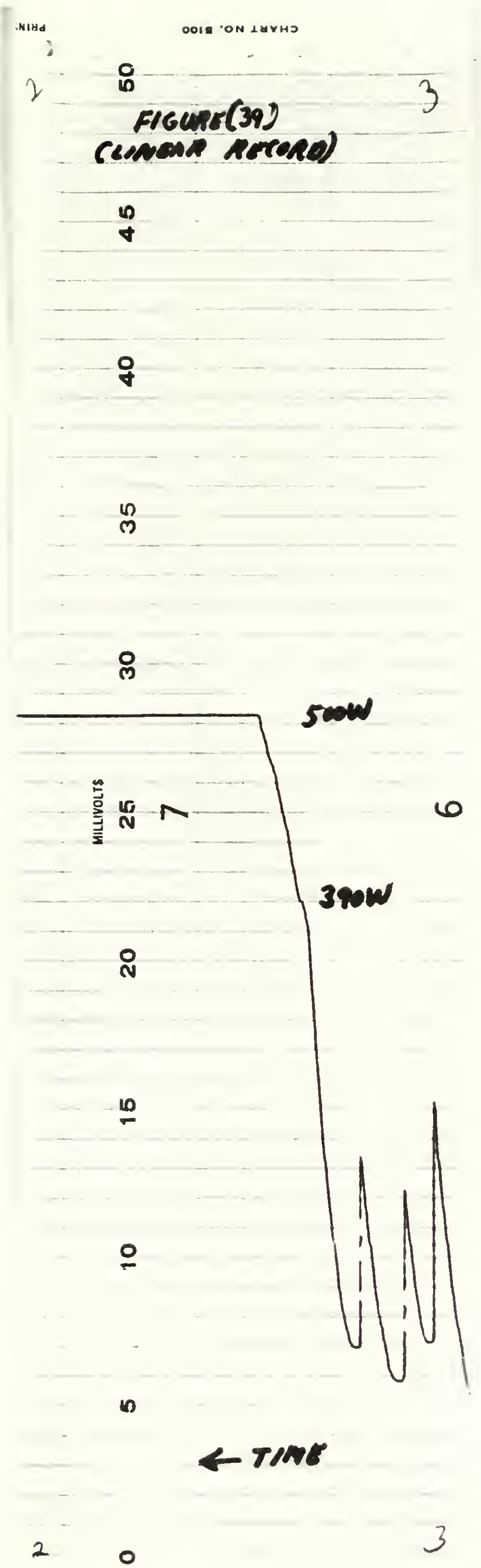


CHART NO. 5874-N
MINNEAPOLIS-HONEYWELL REG. CO., BROWN INSTRUMENT
FIGURE
30 SECOND DEMAND PERIOD
300
NF 100
10
NL 1
.1
.01
.001
.0001
← 550W
← 390W
POWER →
← TIME (1DIV=1MIN)
PLATE 460 PRINTED IN U.S.A.



FIGURE(39)
(LINEAR RECORD)

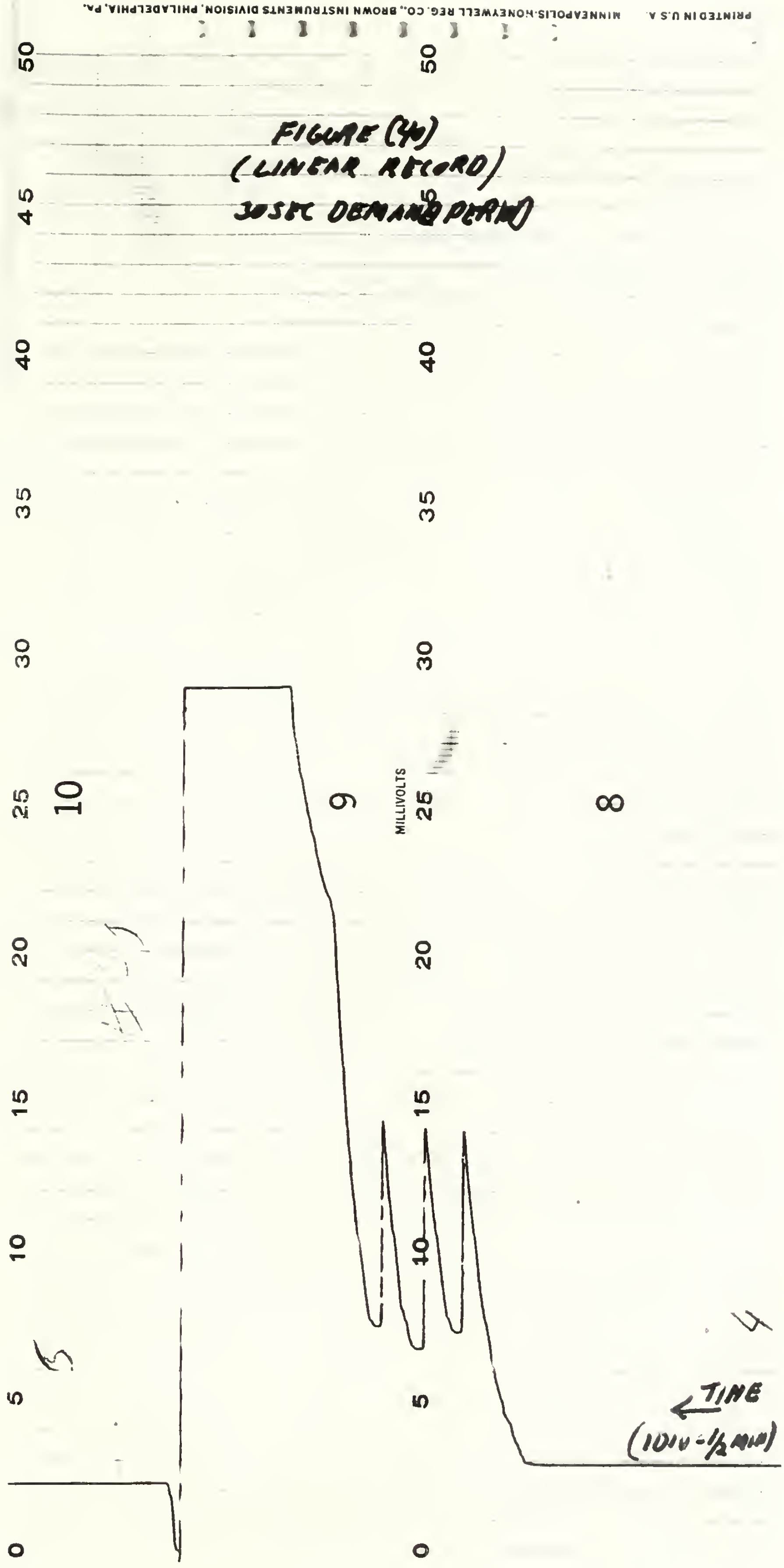


FIGURE (40)
(LINEAR RECORD)
30SEC DEMAND PERIOD
MILLIVOLTS
TIME
(1DIV-1/2MIN)
PRINTED IN U.S.A. MINNEAPOLIS-HONEYWELL REG. CO., BROWN INSTRUMENTS DIVISION, PHILADELPHIA, PA.

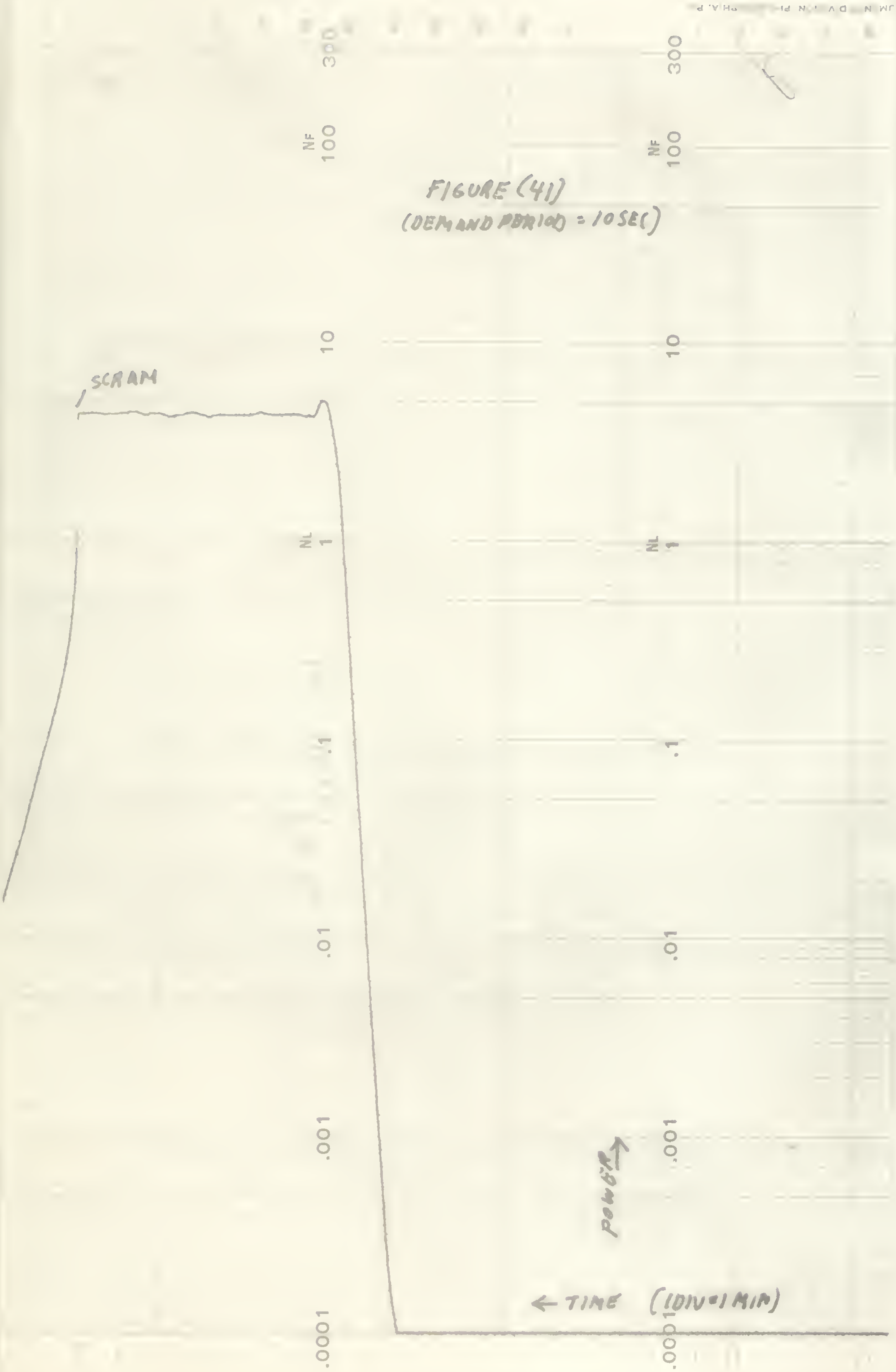


FIGURE (41)
(DEMAND PERIOD = 10 SEC)

a 10-second demanded period because of the limited time available for the experiment. With additional experience, it is believed that the 110 watt overshoot could be greatly reduced by proper setting of the switching levels.

Because of the low rate at which reactivity may be decreased or increased by the automatic control system when using only the regulating rod, it is necessary to start the period run-up at a low level (about 10 watts) when a period as fast as 10 seconds is demanded to prevent excessive power overshoot, thus the period is being increased continuously during the final one-and-one-half decades.

E LOG P RUN

In Figure 42 are shown two restarts. Restart #1 was accomplished using Per - Log P control. The overshoot encountered can be reduced by more accurate setting of the switch point. Restart #2 was accomplished using Per - Lin P control. The point of interest here is the comparison of the traces when on lin P control and on Log P control. It is seen that when Lin P is the controlled variable, there is evidence of drift in the log N amplifier.

F MULTIDECADE LOG P CONTROL

Figures 43 and 44 show multidecade Log P control. It is seen that by using Log P control the power level may be stepped down to any level from 500 watts to about 0.02 watts automatically and held automatically at a demanded power level in that range.

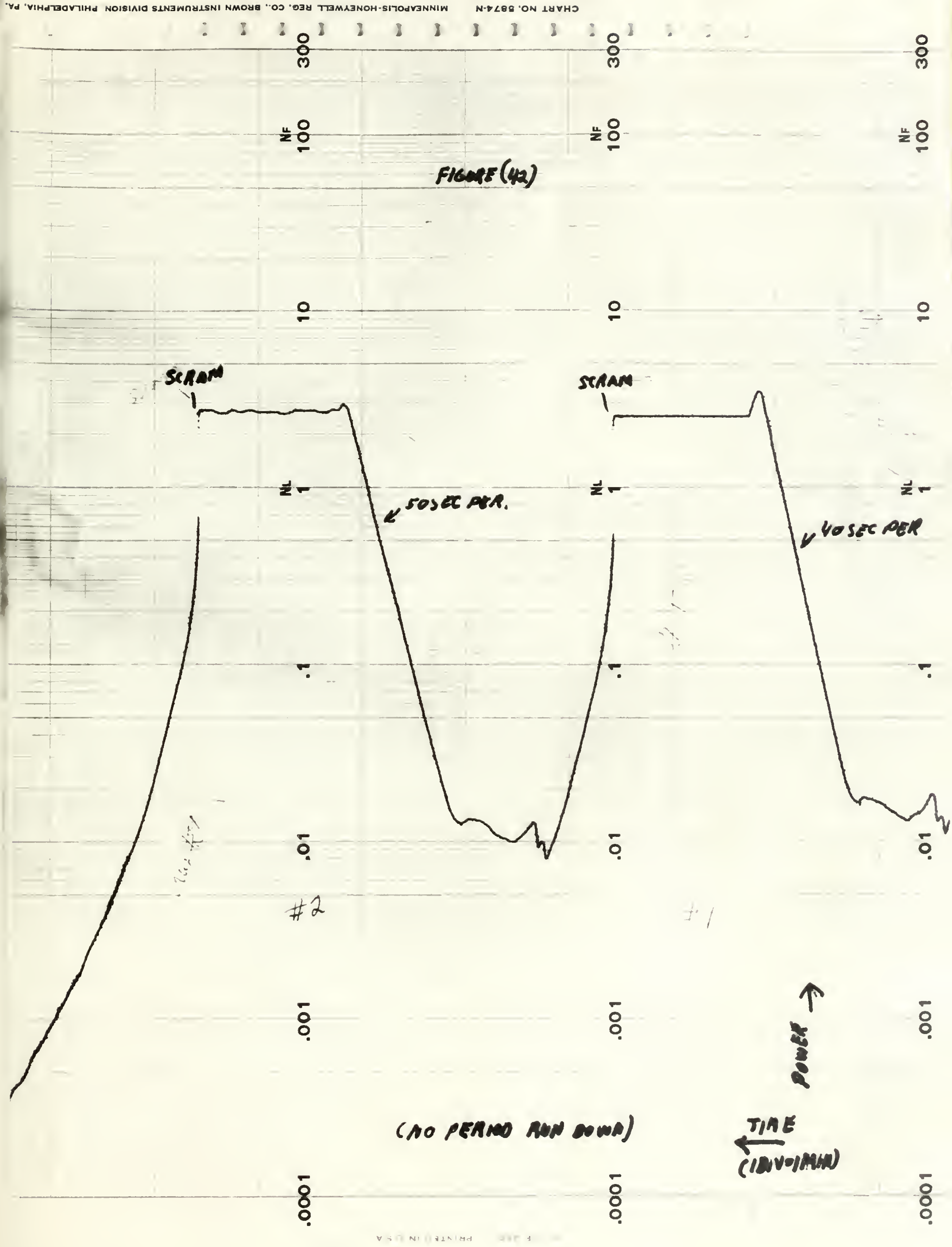

SCRAM
50 SEC PER.
SCRAM
40 SEC PER
#2
POWER
(NO PERIOD RUN DOWN)
TIME
(1 DIV = 1 MIN)
CHART NO. 5874-N MINNEAPOLIS-HONEYWELL REG. CO., BROWN INSTRUMENTS DIVISION PHILADELPHIA, PA.

FIGURE (42)

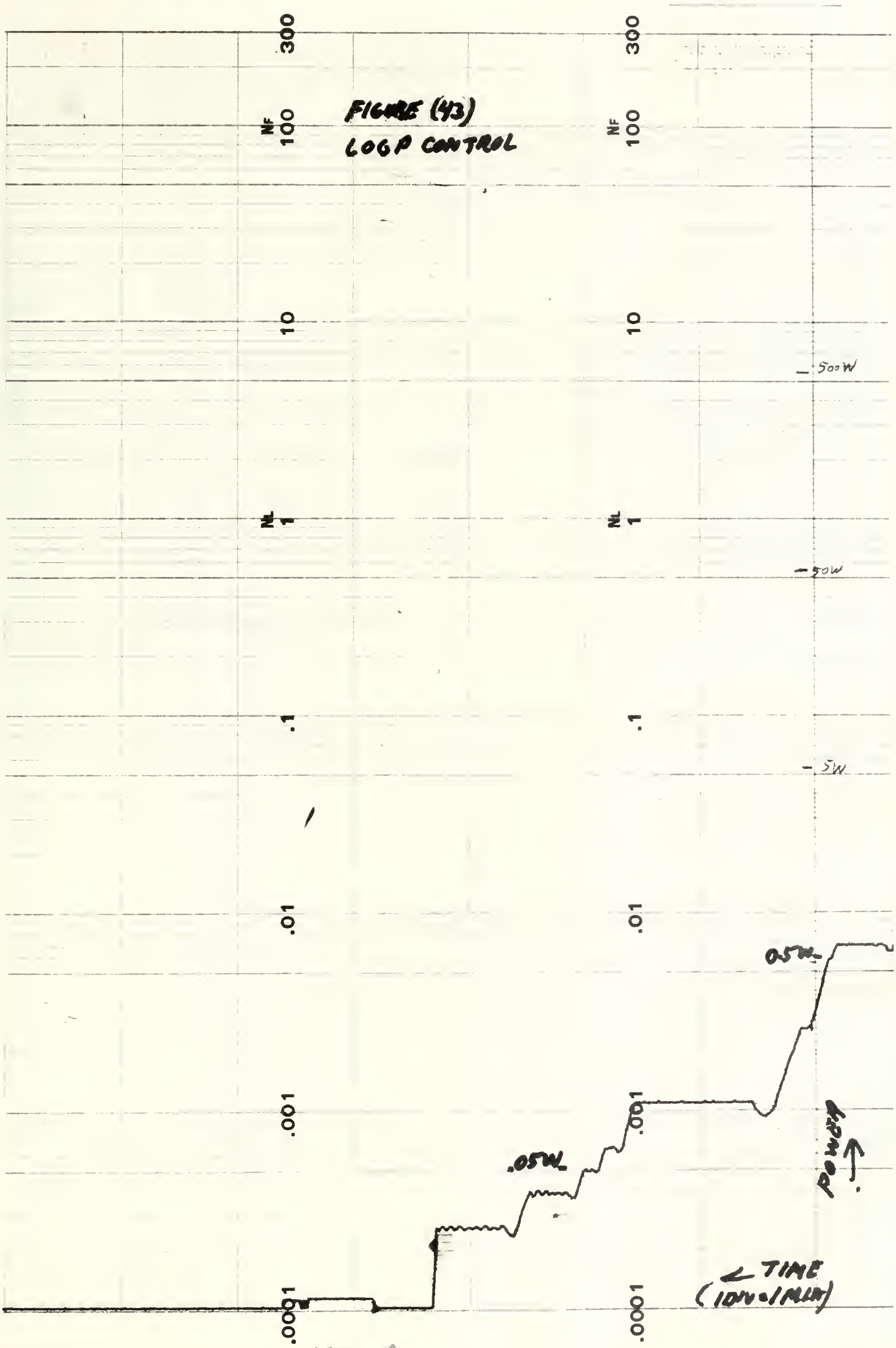


FIGURE (43)
LOGP CONTROL

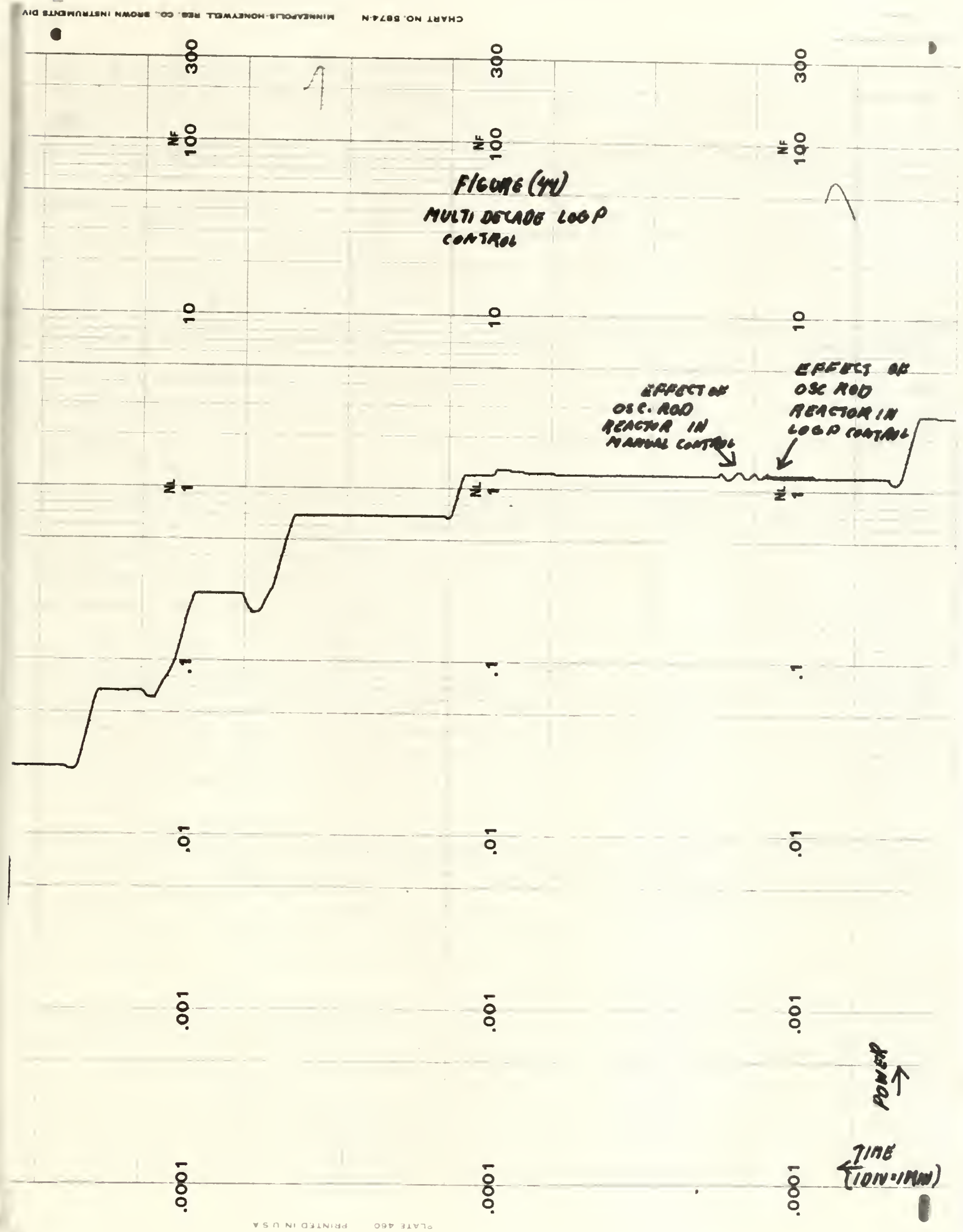


FIGURE (44)
MULTI DECADE LOOP CONTROL

G USE OF COARSE ROD TO DECREASE REACTIVITY:

An attempt was made to cause the coarse control rod to furnish "negative booster" action in the vicinity of demanded power so as to allow a fast period rise to full power with a minimum of power overshoot.

The following techniques were attempted:

1. By setting RE 1 low limit contact before that of RE 5 a signal was available to start the coarse rod in before full power was reached. Activation of Re 5 switched control to Lin P and stopped the coarse rod. This technique did not reduce the overshoot substantially in that the fine rod compensates for coarse rod movement in an attempt to maintain the demanded period. Moreover, calibration problems are acute in that if the coarse rod be too effective, relay 5 low limit contact would be prevented from making and the reactor would overshoot on period control and slowly shut down as the coarse rod was continued to the fully in position.

2. By allowing RE 5 to actuate both fine rod in and coarse rod in motion, it was hoped to reduce the power overshoot. RE 1 upper limit contact was then used to stop the coarse rod. This involved one new feature, namely the activation of the pull-in feature of the high limit contact of RE 1 after the Log P error was sufficiently reduced to prevent premature holding of the relay swinger. This was done by incorporating a spare set of RE 5 A contacts in the coil circuit of relay 1A.

This feature required extremely accurate calibration and

was not practical in that the fine rod feedback control system would not allow the lo P error to increase sufficiently below that demanded by linear P control to actuate the coarse rod stop relay until the worth of the fine rod was reduced as the extremity of the rod became the controlling feature.

The result is a negative or reverse overshoot in reactor power level.

A third attempt involved a combination of the above listed methods in that coarse rod motion was initiated by relay 5 and stopped by low limit contact of relay 1. This required careful calibration in that insufficient overshoot caused the reactor to shut down.

All three of these methods were abandoned in favor of an inverse period run-up system which has been described.

The results of fine rod plus "negative booster" coarse rod control are presented in Figure 45.

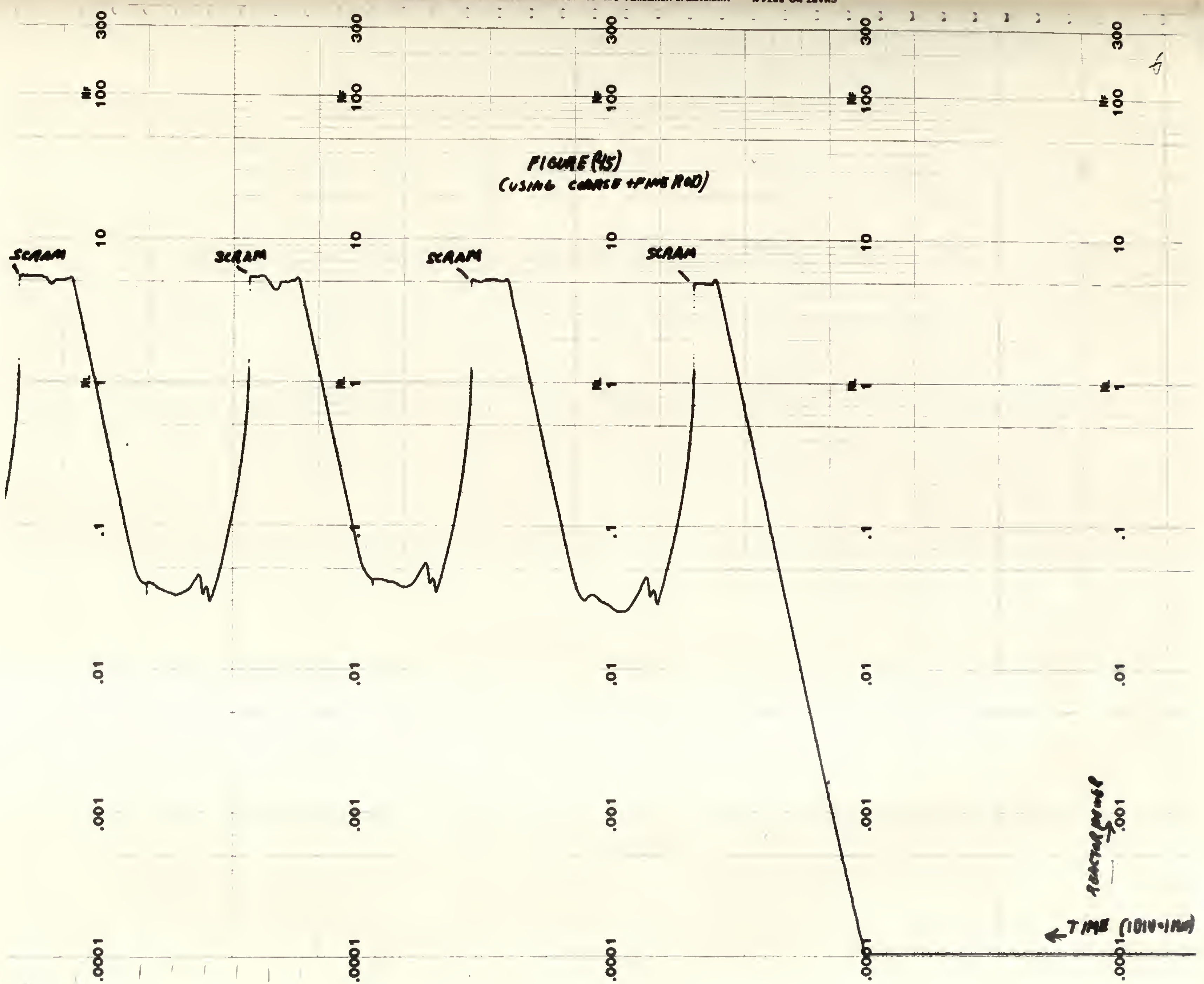


FIGURE (45)
(USING COARSE + FINE ROD)

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Glossary of Symbols:

a - a constant
b - a constant
C - capacitance, capacitor
GIC - Gamma compensated ionization chamber
D - detector constant
G - gain
$H(j\omega)$ - frequency dependent part of a transfer function
I - current
K - a constant, open loop gain, reactivity
K_a - servo amplifier AC gain
K_a' - servo amplifier current to voltage conversion factor
K_c - regulating rod transfer function (percent K)
K_I - IC transfer function
K_M - control motor gain constant
K_N - Log N amplifier gain constant (Log N channel)
K_r - regulating rod transfer function (dollars)
K_R - reactor gain constant
K_1 - servo amplifier gain
KG - transfer function
KG' - open loop transfer function
K_{AN} - attenuator (comparator) transfer function
k - a constant
k_1 - a constant
k_2 - a constant
k_3 - a constant
k_4 - a constant
k_5 - a constant
ℓ - the effective neutron generation time in the reactor
Lin P - linear power
Log P - logarithm of power
m - slope of a line
n_{o1} - number of thermal neutrons per cm^3 per watt
n_o - number of thermal neutrons per cm^3
OLTF - open loop transfer function
P - reactor power
P to P - peak to peak
PER - reactor period
R - resistance
T - reactor period, a time constant
T_A - servo amplifier time constant
T_R - reactor time constant
T_d - Log N amplifier time constant (PER channel)
T_I - indicated reactor period
T_M - control motor time constant
T_N - Log N amplifier time constant (Log N channel)
T_p - Log N amplifier time constant (PER channel)

T_1 - reactor time constant
t - time
V - Voltage
V_c - califration voltage
V_o - output voltage
V_p - voltage proportional to log P
$\cdot$ - control rod position
β_{eff} - effective total fraction of all neutrons which are delayed
β_i - ith group fraction of total neutrons from fission
δ - increment
λ - "one neutron group" decay constant
λ_i - ith neutron group decay constant
φ - neutron flux in the reactor
ω - angular frequency, reciprocal time constant
ω_A - 1/TA
ω_b - break frequency

$$(\quad)^* \frac{(\quad)}{\beta_{eff}}$$

APPENDIX II

MEASUREMENT OF THE POWER TRANSFER FUNCTION OF THE L-3 WATER BOILER NUCLEAR REACTOR

Introduction.

A very thorough discussion of the transfer function of the water boiler reactor is contained in Ref. 17. An inspection of Figures 1, 2, and 3 of Ref. 17 indicates that the highest break frequency is

$$\omega_b = \frac{1}{\ell^*} \tag{1}$$

for P_0 not too large.

Obviously then, if the transfer function can be measured in the vicinity of this frequency, it will be possible to experimentally determine ℓ^*, the normalized effective neutron generation time in the reactor.

Furthermore, since the transfer function had not been experimentally determined for the L-3 waterboiler, the objective of the measurement could be broadened to include measurement of the transfer function over as wide a frequency range as possible.

Initially four methods were considered:

1. Construction of a pile oscillator and experimental determination of the transfer function over as wide a frequency range as the mechanical components of the pile oscillator would allow. This is the classical method of Harrer, Boyar, and Drucoff as used on the CP-2 reactor and outlined in Ref. 5.

2. (a) The use of a statistical technique as outlined

in Ref. 6a whereby white noise is applied to the reactor and the crosscorrelation function between the input and output is measured. Since this crosscorrelation function is the system response to an impulse, it is necessary to numerically take the Fourier transform of the measured crosscorrelation function. There are major instrumentation difficulties here, such as obtaining the noise generator which has a flat noise spectrum over the frequency range of interest and obtaining a crosscorrelator with the proper frequency response. Moreover, once the noise generator is obtained there is the difficulty of applying it to the reactor.

(b) These difficulties are for the most part alleviated by the procedure outlined in Ref. 6. By this technique, it is only necessary to measure the autocorrelation function for power noise in the reactor to obtain the weighting function or rector response to a unit impulse. However, there is still the need for a correlation device.

3. Direct application of an impulse to the reactor and measurement of the response was considered. Serious objections here involve the difficulty of physically obtaining a good approximation to an impulse.

4. Application of a step function to the reactor, numerical differentiation of the response and a subsequent Fourier transform to obtain the transfer function. The main objection here is the limited accuracy imposed by the instrumentation whereby the response is determined.

Since the equipment necessary for construction of a pile

oscillator was already available, this method was chosen for the first attempt. The pile oscillator design specifications were jointly determined by Mr. Fred Shon and Mr. Ernest Hill of UCRL, Livermore, California. The implementation of this design was accomplished by Mr. William Wade. The instrumentation finally adopted was developed by the author based upon the method outlined in Ref. 5, and suggestions of Mr. Fred Shon andMr. Gordon Nelson. The operating crew and electronics staff of the LPTR assisted in the setting up and operation of the experiment.

Description of the Experiment.

A. The Pile Oscillator.

The pile oscillator moved a $2cm^2$ strip of cadmium with simple harmonic motion in the glory hole of the L-3. The peak to peak amplitude of oscillation was two inches, so chosen that the perturbation introduced by the cadmium would only occur in that section of the reactor core where the importance function was approximately linear with distance from the center of the core. Figure 1-I is a sketch of that part of the pile oscillator inside the reactor core.

The mechanical construction of that part of the pile oscillator external to the reactor is shown in Figures 2-II, 3-II, and 4-II. Figure 2-II shows the point of entrance of the oscillator rod into the reactor shielding as well as the aluminum mounting and support table and brackets.

Figure 3-II shows the scotch yoke assembly whereby the rotational motion of the variable speed motor shaft was

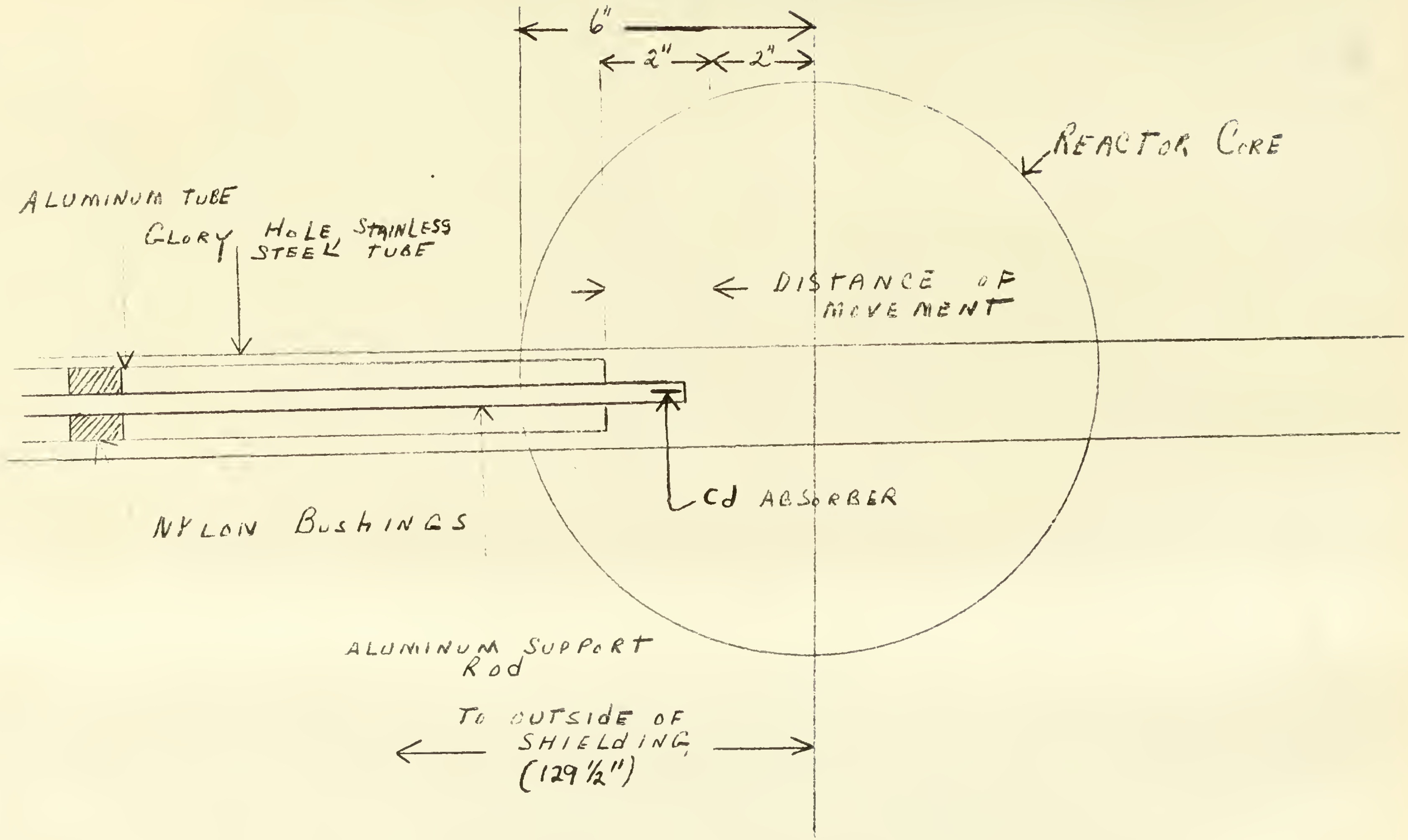


FIGURE I - APPENDIX II

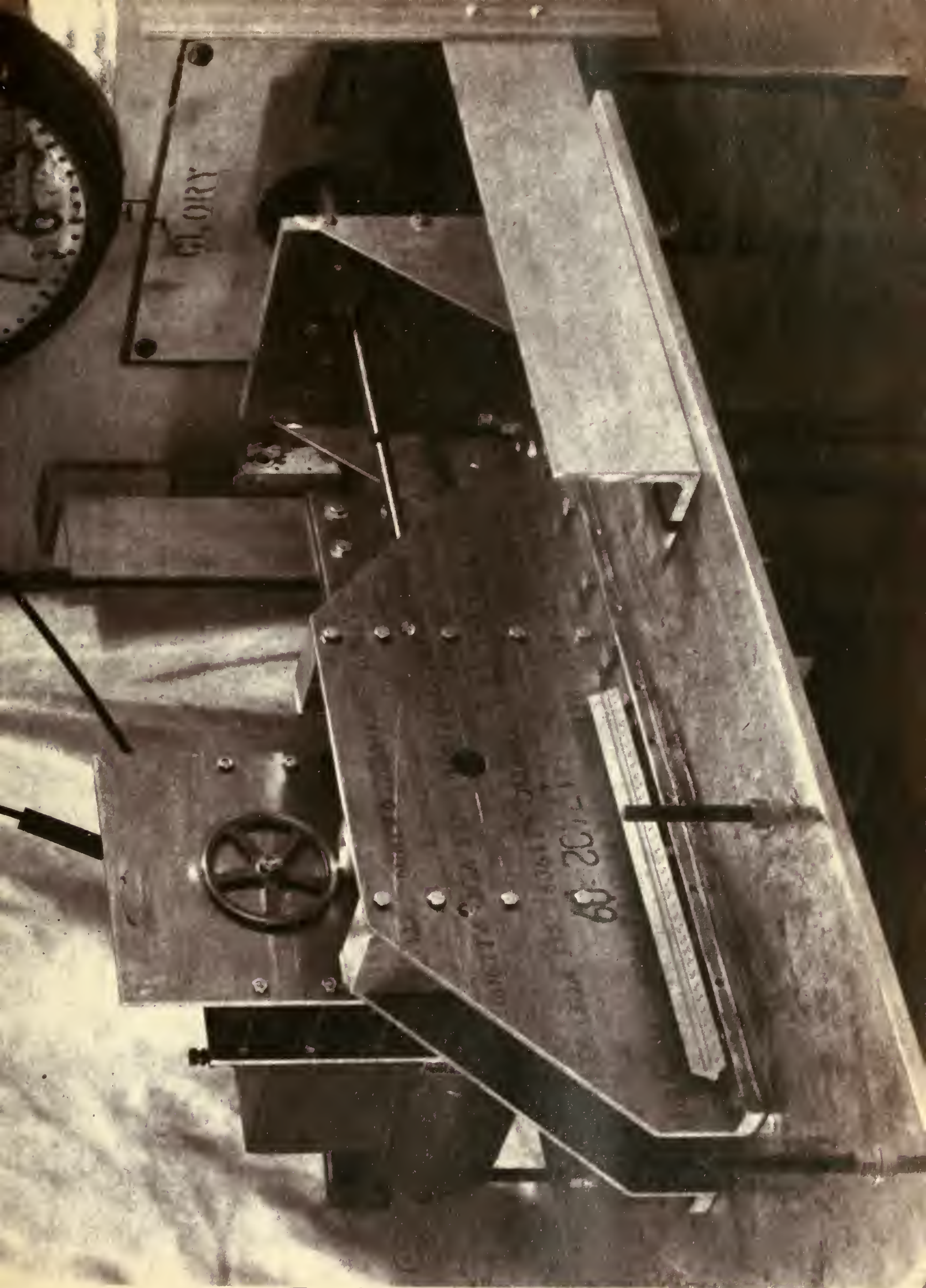


FIGURE 2-II (COURTESY LAWRENCE RADIATION LABORATORY)

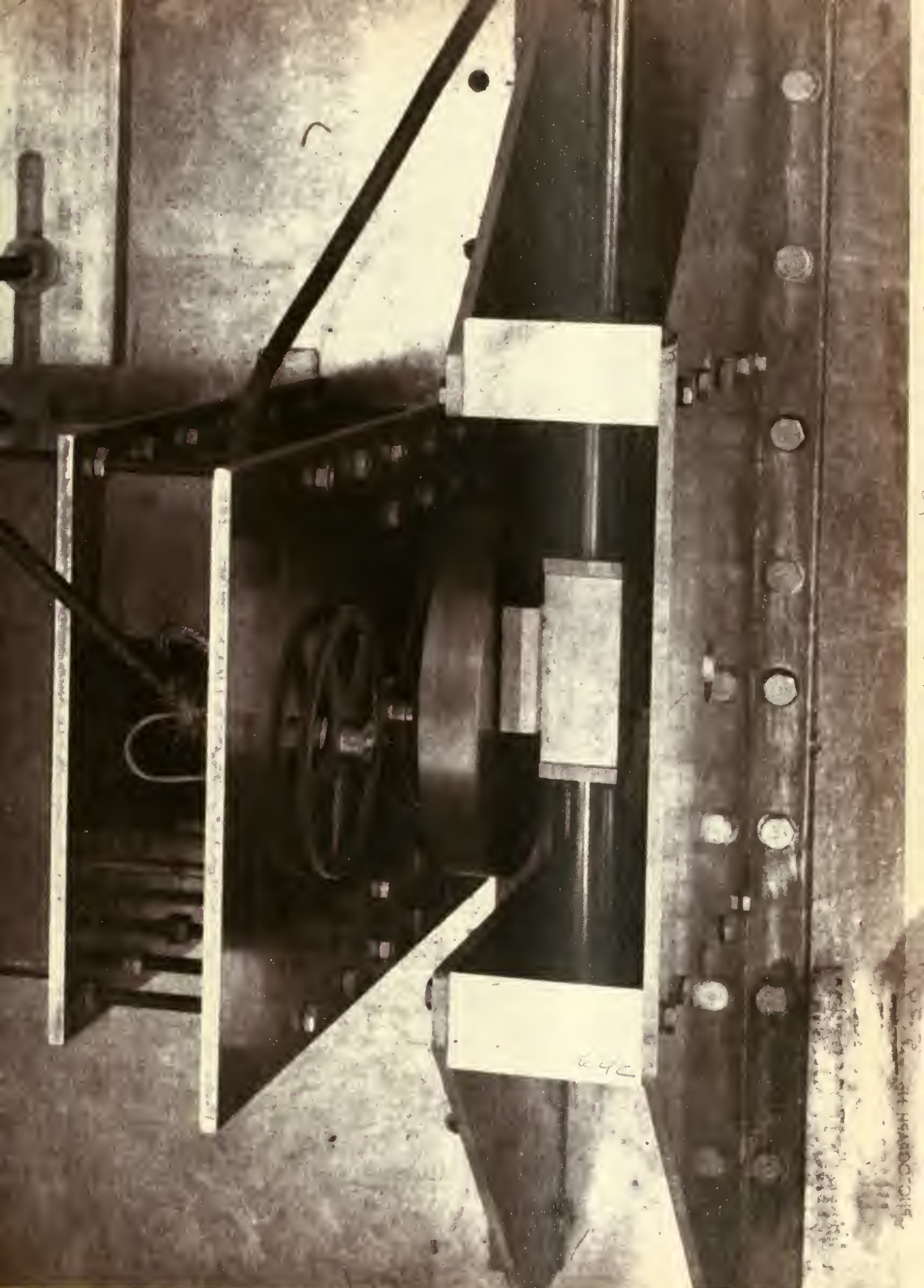


FIGURE 3-11 (COURTESY LAWRENCE RADIATION LABORATORY)

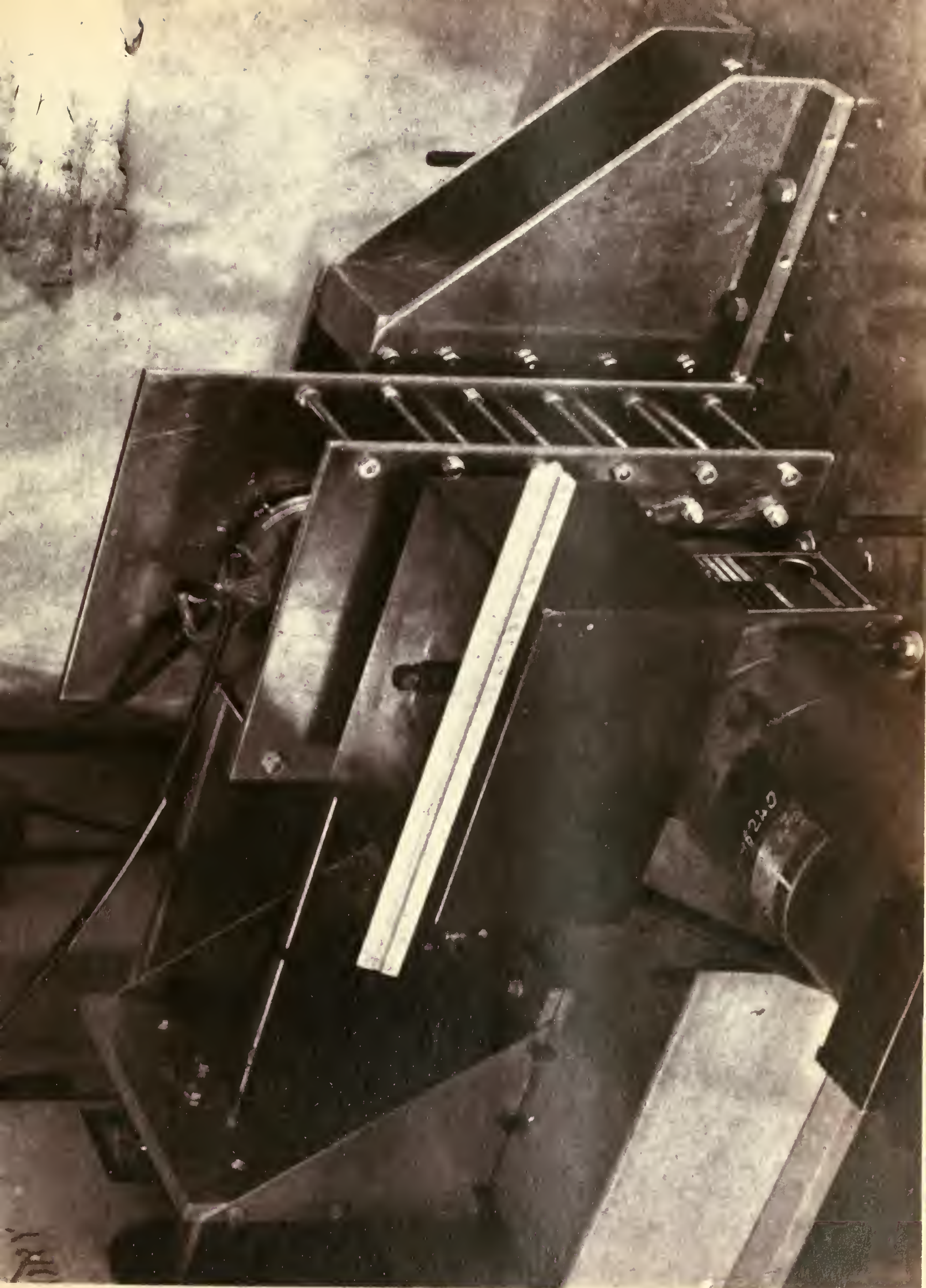


FIGURE 4-II (COURTESY LAWRENCE RADIATION LABORATORY)

converted to simple harmonic motion of the oscillator rod to provide for a sinusoidal variation of reactivity. The amplitude of variation was fixed by stroke length and was designed to be small in order to not exceed the linearity requirements associated with the definition of the transfer function. However, the amplitude of reactivity variation could be changed by the insertion of cadmium absorbers of different areas. The brackets attaching the table to the reactor were constructed with adjustable slots to allow optimum positioning of the oscillator rod in the glory hole.

Figure 3-II also shows the 1:1 gearing arrangement whereby the swinger of a one turn helipot was geared to the oscillator rod drive. This helipot was used to generate a sawtooth waveform to provide both frequency and phase information.

Figure 4-II shows the variable speed motor and gearbox which was used to drive the oscillator rod at speeds from 0.076 to 157 radians/sec. Also shown is the helipot from which phase and frequency information was obtained.

B. Instrumentation.

A schematic representation of the instrumentation used is shown in Figure 5-II.

The two channel recorder was used at the lower frequencies to determine frequency and phase between input and output signal as a function of frequency. At the higher frequencies the two channel recorder was used to determine frequency and relative amplitude of the output signal, but not phase information because of the limited paper speed of

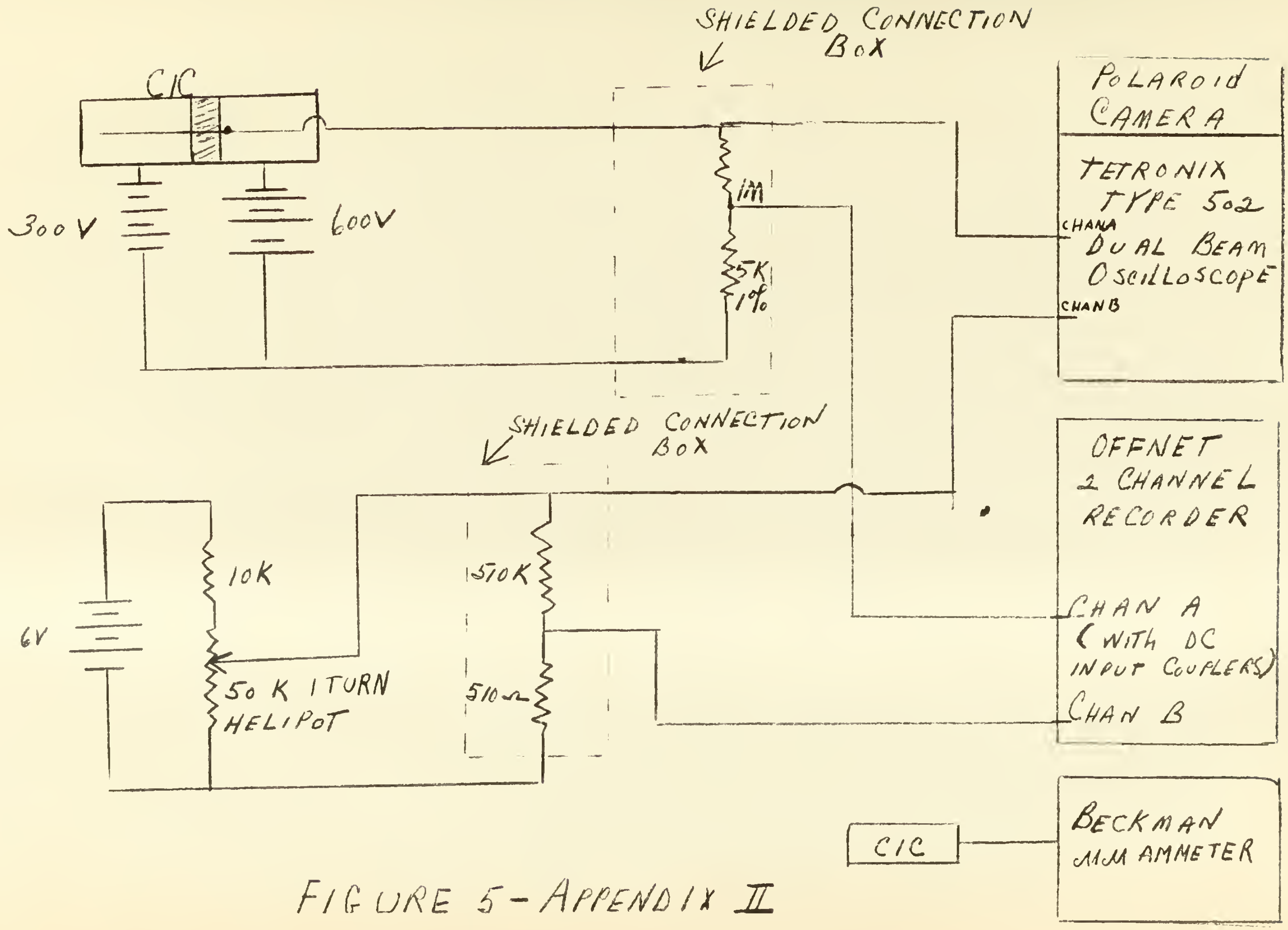


FIGURE 5 - APPENDIX II

the recorder. Phase information and frequency were determined at the higher frequencies, by using the dual beam oscilloscope and polaroid camera.

In order to determine the steady state power level during the measurements, an accurately calibrated Beckman micromicroammeter was used.

To convert from relative to absolute amplitudes the worth of the oscillator rod was determined by a calibration against the fine control rod, the worth of which is accurately known. It was also necessary to know the transfer function of the CIC and coupling network and the calibration of Channel A of the Offnet recorder.

The CIC used is the CIC with optimum placement with respect to the reactor core (the Servo Amp. Lin-P CIC).

C. Sample Calculations.

Figure 6-II gives equivalent circuits for CIC and coupling circuitry to the recorder and oscilloscope. The input impedance of the oscilloscope and the recorder, as well as cable and CIC capacitance, measured by means of MOD 250 DA Impedance Bridge, is accounted for.

Figure 6(a)-II is the general equivalent circuit. The magnitude of the current I_2 is known to be 0.05 microamp/watt reactor power.

The values of resistance indicated are specified to the order of magnitude that they are known. A consideration of Figure 6(a)-II will indicate that $|I_1| \cong |I_2|$ to the order of magnitude that the variable and circuit parameters are known.

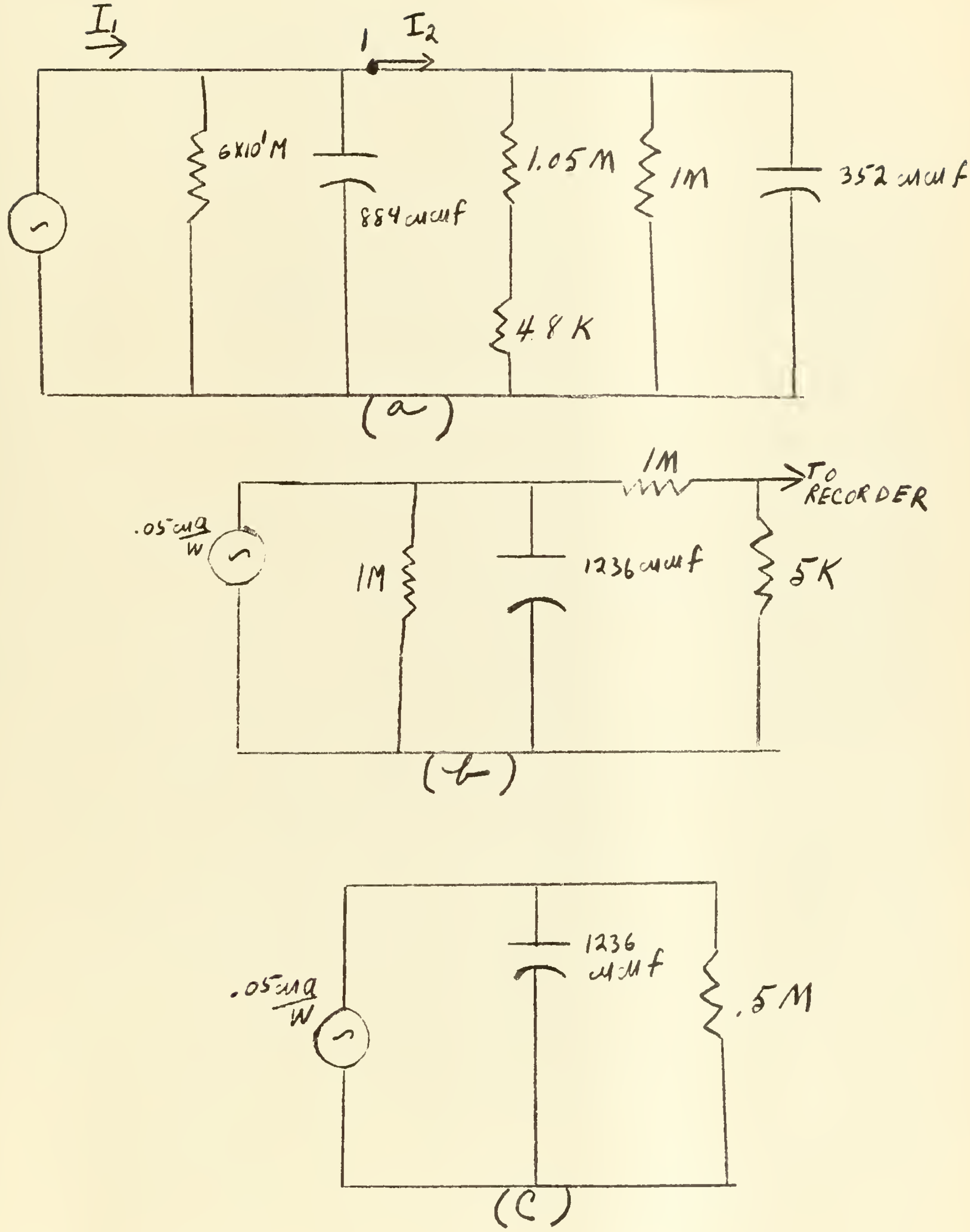


FIGURE 6 – APPENDIX II

Figure 6(b)-II is an equivalent circuit appropriate for consideration of current division in so far as magnitude of the output signal is concerned. Thus to the accuracy of the data the effective magnitude of the transfer function from reactor to recorder input is 0.025 μa/watt over the frequency range of interest.

Figure 6(c)-II is an equivalent circuit appropriate for consideration of phase shift from reactor to oscilloscope.

Phase shift $\phi = -\arg(1+j\omega T)$

where $T = RC = 0.5 \times 10^{6} \times 1236 \times 10^{-12} = 618 \times 10^{-6}$ (2)

$T = 6.18 \times 10^{-4}$ sec. (3)

Figure 7-II is a plot of phase lag in the detector circuitry as a function of frequency.

Conversion, Relative to Absolute Gain:

Pile OSC Expt. 2/19/59. (Table 4-II)

Input: 0.057 dollars peak to peak worth of oscillator rod.

Output:

V_C = calibration voltage of dynagraph = $\frac{1 \text{mV}}{7.3 \text{ mm}}$

CIC Constant = 5.0×10^{-8} amp/watt reactor power

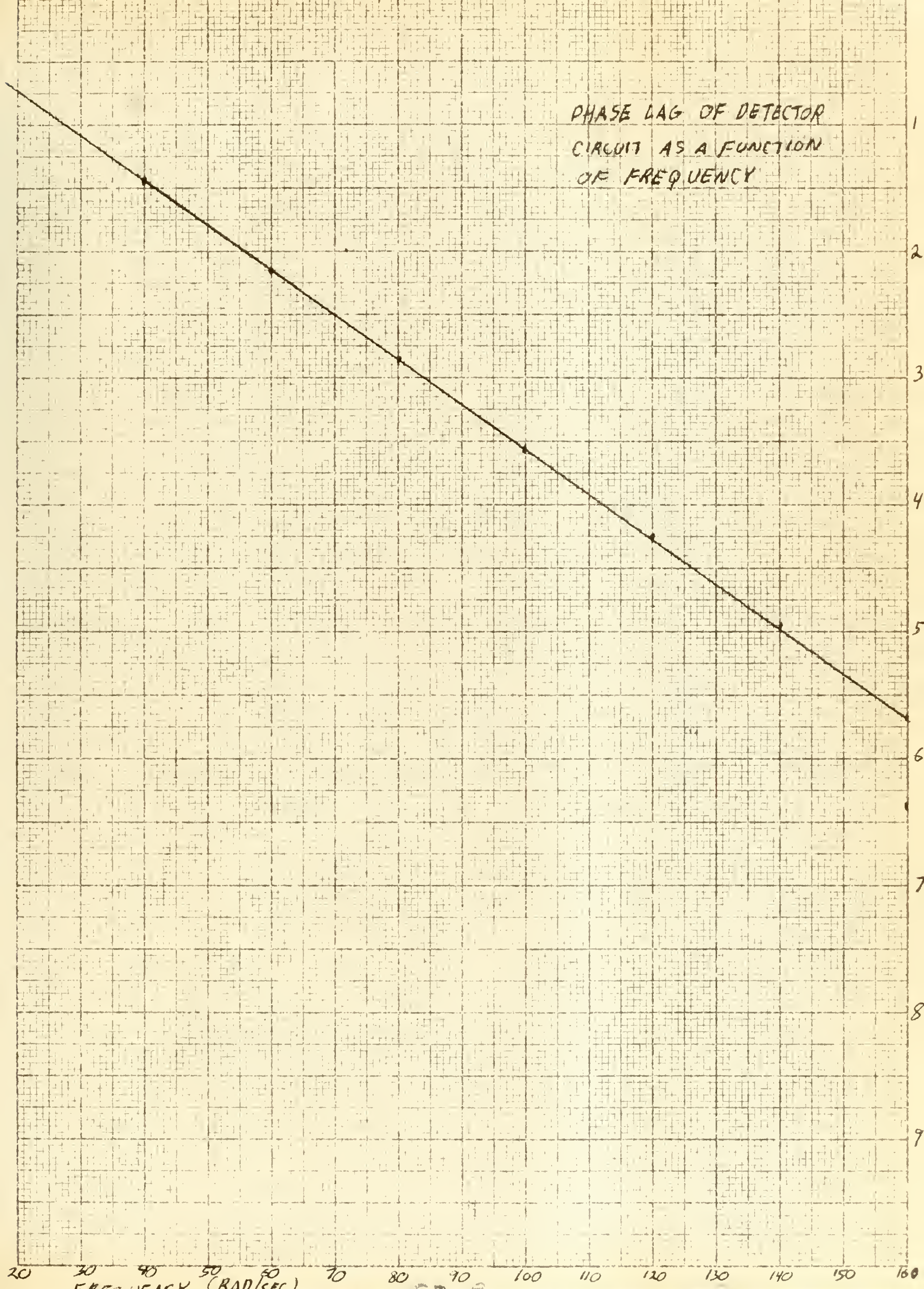
Detector Constant, D

$D = 4.7K \times \frac{5.0 \times 10^{-8}}{2} = 1.17 \times 10^{-4}$ volt/watt

$P_o = 459.W$ ($1.35 \times 10^{-6}_{a}$ Beckman #1)

For chart sensitivity used

$DV_C = 0.117 \frac{mv}{w} \times 7.3 \frac{mm}{mv} = 0.854 \frac{mm}{w}$


PHASE LAG OF DETECTOR
CIRCUIT AS A FUNCTION
OF FREQUENCY
1
2
3
4
5
6
7
8
9
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
FREQUENCY (RAD/SEC)

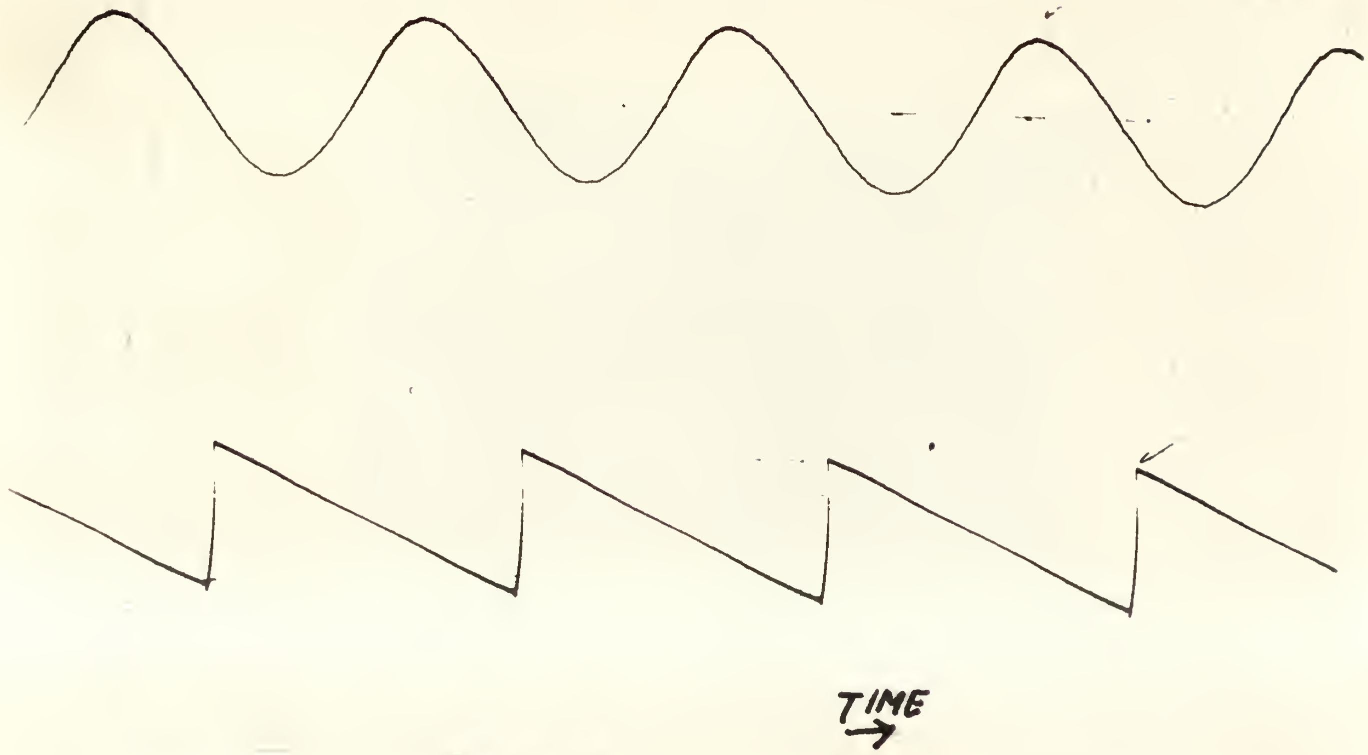


FIG II-8

FIGURE 9-II

$$\text{Gain} = \frac{\text{Vout P to P (mm)}}{0.854 \text{ mm } P_{DC} \times \Delta K_{P \text{ to } P}} \tag{4}$$

At 0 db relative

$$\text{Gain} = \frac{23.2}{0.854 \times 459 \times 5.7 \times 10^{-2}} = 1.04 \tag{5}$$

20 log Gain Factor = 20 log 1.04 = 0.32 db

In Figures II-8 and 9-II, samples of the measured data are shown. Figure 10-II is a plot of the magnitude of the reactor transfer function. Figure 11-II is a plot of the argument of the reactor transfer function.

The reactor is herein treated as a minimum phase network in that either Figure 10 or Figure 11 is sufficient to determine the transfer function. It is noteworthy that the prompt neutron lifetime as determined from either plot is substantially the same value.

$$l^* = \frac{1}{\omega_b} = \frac{1}{74} = 1.35 \times 10^{-2} \text{ sec} \tag{6}$$

If we assume $\beta_{eff} = 0.00855$

$$l = l^* \beta_{eff} = 1.155 \times 10^{-4} \text{ sec} \tag{7}$$

This value of 1* will be used in both the linear analysis and computer 5-delayed-neutron-group analysis of the control system being designed.

$$DV_C = 0.117 \frac{mV}{W} \times 24 \text{ mm/mv} = 2.81 \text{ mm/w}$$

$$\text{Gain} = \frac{\text{V out P to P (mm)}}{2.81 \frac{mm}{W} P_o \times \Delta K_{P} \text{ to P}} \tag{4}$$

$$\text{Gain} = \frac{V_{out}}{2.81 \times P_o \quad \times 5.7 \times 10^{-2}} = \frac{6.24}{P_o} V_{out} \tag{8}$$

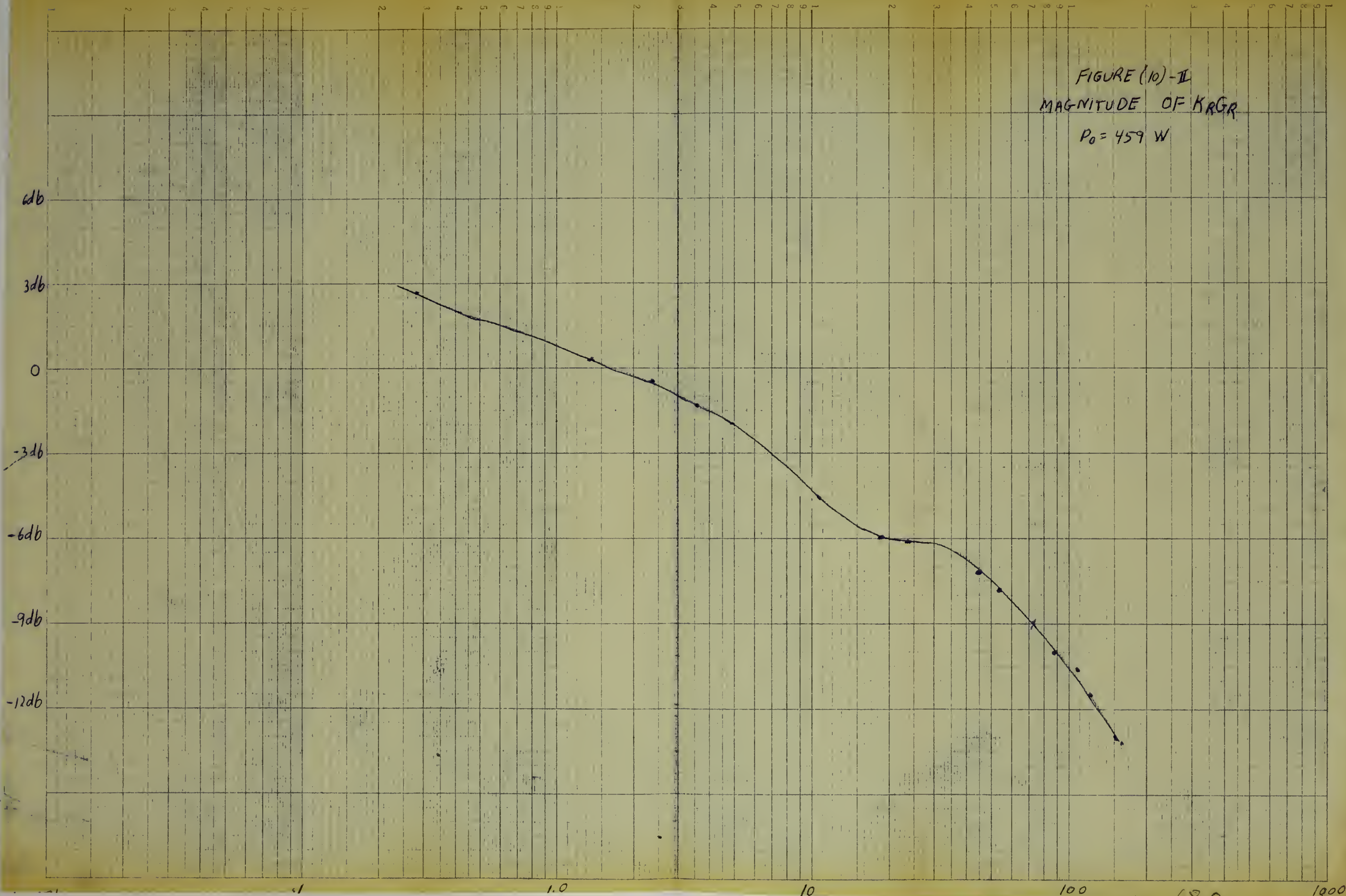


FIGURE (10)-II
MAGNITUDE OF $K_R G_R$
$P_0 = 459$ W
6db
3db
0
-3db
-6db
-9db
-12db
.1
1.0
10
100
1000

68-a

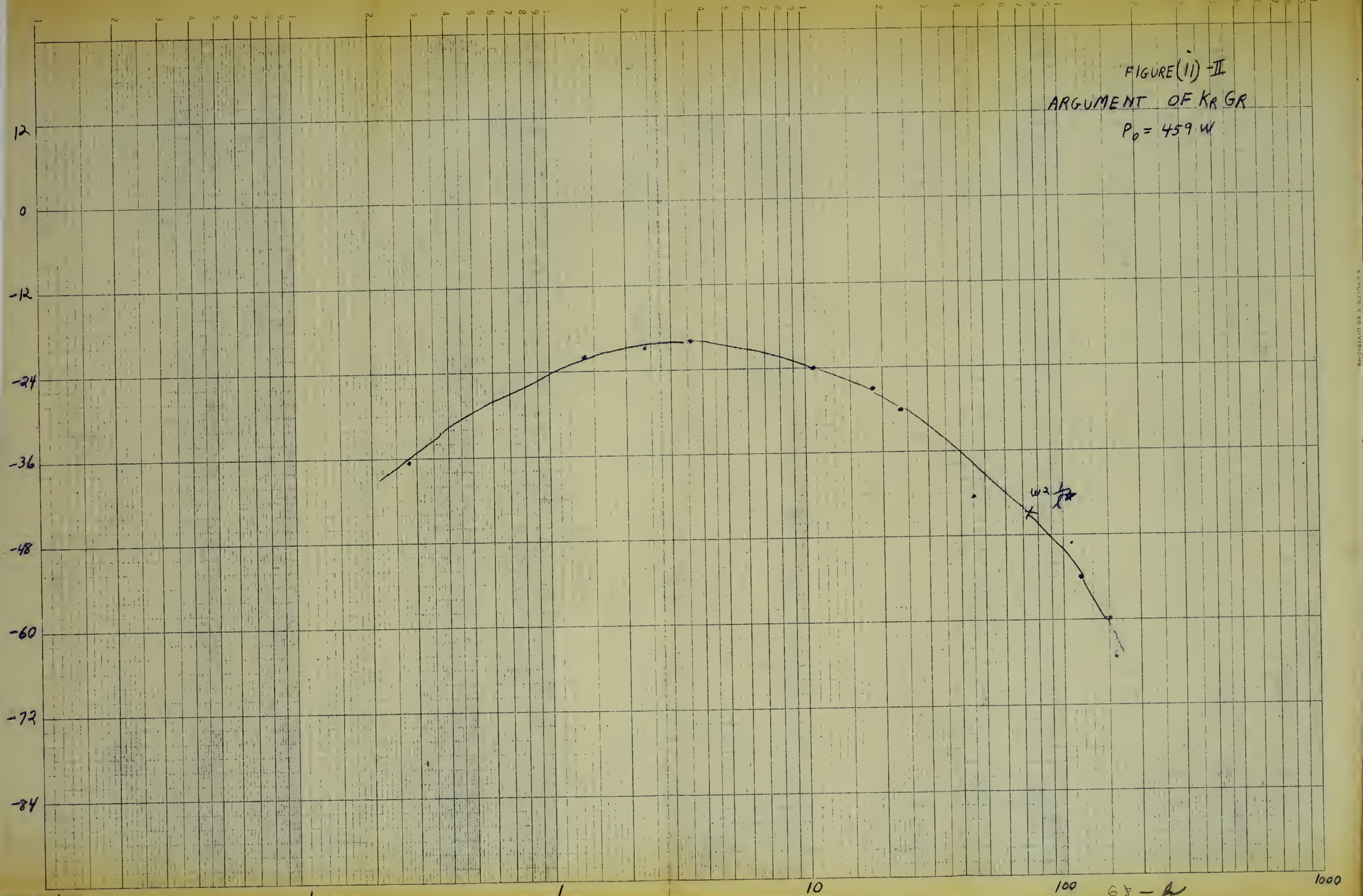


FIGURE (ii) -II
ARGUMENT OF $K_R G_R$
$P_0 = 459$ W
12
0
-12
-24
-36
-48
-60
-72
-84
.1
1
10
100
1000

68-

TABLE I-II

OSCILLATOR ROD CALIBRATION

Rod Position	ΔK(%)	ΔΔK(%)
19.29 cm	.367	
21.95 cm	.317	
		.050
19.67 cm	.357	
22.10 cm	.313	
		.044
19.67 cm	.357	
22.33 cm	.310	
		.047
19.85 cm	.354	
22.33 cm	.309	
		.045
19.85 cm	.354	
22.46 cm	.306	
		.048
19.65	.356	
22.49	.305	
		.051
14.48	.466	
16.95	.418	
	.048	.048
		7/.333
		.0476

PHASE CORRECTION

Rod out Posit 7 3/32" (227)

Start of Ramp 6 1/32"

as the rod moves out, (193)

Rod in Posit. 5 3/32" (163)

$\frac{30}{64}$" from rod in position,

as rod moves out ramp begins ∴ 2/64 lagging 0,

$2/64 \times 360 = 11.2^\circ \cong 11^\circ$

Lead Spaccin Pot $= 2^\circ$

Total Phase Correction from Pt of measurement $= 2 + 11 = 13^\circ$

Readings taken at different core temperatures. Effect of core temperature changes is not within accuracy of the measurement.

$\frac{\Delta K}{\beta_{eff}} = \frac{.0476}{.855} = .057$ dollars peak to peak worth of oscillator rod.

TABLE 2 - II

BECKMAN MICRO MICROAMMETER CALIBRATION

#1

$1W = 3.4 \times 10^{-9}$ amp

$5W = 1.7 \times 10^{-8}$ amp

$10W = 3.4 \times 10^{-8}$ amp

$20W = 6.8 \times 10^{-8}$ amp

$50W = 1.7 \times 10^{-7}$ amp

$100W = 3.4 \times 10^{-7}$ amp

$200W = 6.8 \times 10^{-7}$ amp

#2

$500W = 1.02 \times 10^{-7}$ amp

TABLE 3-II L-3 REACTOR TRANSFER FUNCTION FILE (SC. EXPT 3/17/59

RUN #	PAPER SWEEP SPEED mm/sec	RAMP LENGTH mm	FREQ. CPS	V PHASE CORR.	PHASE LAG DEG	CORR PHASE LAG	DET CORR.	P TO P AMPL	REACT # 2 2×10^6	DC POWER LEVEL	|KG|	LOG KG	20 LOG KG	FREQ RAD/sec	CORR PHASE LAG DEG	REMARKS
1	25	102.2	.244	-13	8.3/102.2 × 360	16.2	—	14.5	1.84	90.5	1.0	-0	0	1.48	16.2	
2	50	39.9	1.26	-13	3.6/39.9 × 360	19.4	—	9.5	1.84	90.5	.655	-.184	-3.68	7.87	19.4	
3	100	40.2	2.49	-13	3.6/40.2 × 360	21	—	8.0	1.84	90.5	.552	-.258	-5.16	15.66	21	
4	100	34.2	3.0	-13	3.8/34.2 × 360	27	.8	7.75	1.84	90.5	.500	-.302	-6.04	18.8	26.2	
5	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
6	100	19.8	5.04	-13	2.4/19.8 × 360	31.2	1.1	6.95	1.84	90.5	.479	-.32	-6.40	31.7	30.1	
7	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
8	100	17.5	5.72	-13	2.3/17.5 × 360	33.2	1.2	6.9	1.84	90.5	.476	-.323	6.52	34.5	32	
9	—	—	—	—	—	—	—	—	—	—	—	—	—	—		
10	100/500	10.9/54.2	9.14/9.13	-13	3.5/27.1 × 360	33.4	2.1	5.6	1.84	90.5	.386	-.414	-8.28	57.5	29.5	
11	100/1000	1.26/40	[illegible]	-13	6/40 × 360	41.0	2.8	5.0	1.84	90.5	.344	-.464	-9.28	76	38.2	
12	100/1000	6.96/62.4	14.5	-13	5.6/33.7 × 360	46.8	3.2	4.6	1.80	88.5	.324	-.490	-9.80	90	43.6	
13	100/1000	5.8/58.6	17.25	-13	5/28.3 × 360	48.5	3.9	4.1	1.80	88.5	.289	-.540	-10.80	108.5	44.6	
14	100/1000	4.76/48	21/20.8	-13°	4.8/24 × 360	59	4.8	3.7	1.80	88.5	.261	-.584	-11.68	132	54.2	
15	100/2000	4.4/90	22.5/22.2	-13°	7.2/45 × 360	60.5	5.0	3.5	1.80	88.5	.257	-.59	-11.90	142	55.5	
16	10	129	.0775	-13°	15/129 × 360	28.8	—	17	1.80	88.5	1.20	+.079	+1.58	.487	28.8	
17	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
18	10	111.5	.09	-13°	12/111.5 × 360	25.8	—	16.9	1.80	88.5	1.192	+.076	+1.52	.565	25.8	
19	50	45.8	1.09	-13°	4.5/45.7 × 360	22.4	—	10	1.79	87.8	.711	-.148	-2.96	6.84	22.4	
20	2.5	141.8	.0176	-13°	21.2/141.8 × 360	40.8	—	28.8	1.86	91.3	1.96	+.294	+5.88	.111	40.8	
21	2.5	138	.0181	-13°	21.2/137.8 × 360	42.4	—	27.5	1.94	95.2	1.80	+.256	+5.12	.114	42.4	
22	1 mm/sec	82.5	.0121	-13°	13/82.5 × 360	43.6	—	32.5	1.9	93.4	2.18	+.340	+6.80	.0762	43.6	

DYNAGRAPH SENSITIVITY 24 mm/mv

12ND 6961

TABLE 4-II   L-5 REACTOR TRANSFER FUNCTION - PILE OSC. EXPT. 2/19/59

RUN #	PAPER (SWEEP) SPEED mm/SEC	RAMP LENGTH mm	FREQ CPS	FREQ rad/SEC	PHASE CORR -130	PHASE LAG DEG	PHASE LAG CORR DEG	PT-P AMPL mm	BECK #1 A×10^6	DC POWER LEVEL WATTS	|KG rel| (RATIO)	20 log KG rel Db	20 LOG GF Db	20 LOG |KG| Db	DET CORR DEG	CORR PHASE LAG DEG
1	2.5	55.8	.0448	.282	-130	$\frac{7.8}{55.8}\times360$	36.6°	30.5	1.35	459	1.315	2.38	.32	2.7	—	36.6
2	10	26.4	.379	2.38	-130	$\frac{1.5}{26.4}\times360$	21°.0	21.2	1.35	459	.913	-.8	.32	-.48	—	21
REF 3	10	45.8	.218	1.37	-130	$\frac{4.5}{45.8}\times360$	22.4°	23.2	1.35	459	1.000	0	.32	.32	—	22.4
4	25	43.6	.574	3.60	-130	$\frac{4}{43.6}\times360$	20°.0	19.3	1.35	459	.831	-1.62	.32	-1.32	—	20
5	50	28.8	1.738	10.9	-130	$\frac{3}{28.8}\times360$	24.4°	13.2	1.35	459	.569	-4.92	.32	-4.59	—	24.4
6	100	34	2.94	18.45	-130	$\frac{3.8}{34}\times360$	27.2°	11.2	1.35	459	.483	-6.32	.32	-6.0	.5	26.7
7	100	26.5	3.78	23.7	-130	$\frac{3.2}{26.5}\times360$	30.5°	11.0	1.35	459	.474	-6.5	.32	-6.18	.75	29.65
8	100	14	7.14	44.8	-130	$\frac{2.2}{14.1}\times360$	43°	9.8	1.35	459	.423	-7.48	.32	-7.16	1.6	41.4
9	100	11.6	8.61	54	-130	$\frac{1.8}{11.6}\times360$	42.5°	9.0	1.35	459	.388	-8.24	.32	-7.92	1.9	40.6
10	100/1000	7/70.2	~~14.3~~/14.28	~~89.8~~	-130	$\frac{5.7}{35.1}$	45.5	7.0	1.35	459	.302	-10.4	.32	-10.08	3.2	42.3
11	100/1000	5.8/58	~~17.25~~/16.95	~~108~~ 106.5	-130	$\frac{11.6}{58}\times360$	52.6	6.6	1.35	459	.284	-10.96	.32	-10.64	3.6	49
12	100/1000	5.25/52	~~19.1~~	~~119.8~~	-130	$\frac{10.4}{52}\times360$	58	5.9	1.35	459	.254	-11.9	.32	-11.58	4.2	53.8
13	100/2000	4 16/80	~~24.2~~/25.0	~~151.5~~	-130	$\frac{8.7}{40}$	65	5.0	1.35	459	.216	-13.3	.32	-12.98	5.35	59.65
14	100/2000	3.96/79.6	~~25.1~~/25.2	~~158.5~~	-130	$\frac{9.3}{37.8}$	71	4.9	1.35	459	.211	-13.5	.32	-13.18	5.6	65.4

DYNAGRAPH SENSITIVITY $7.3 \frac{mm}{mV}$

D. Discussion of Results.

Figure 12-II is a plot of the argument of K G based on data taken with $P_0 = 90W$. The shape of the curve is similar to that shown in Figure 11-II, but the curve seems to be displaced about two degrees from that of Figure 11-II. The data upon which Figure 11-II is based is considered to be more accurate at the high frequencies because of noise present on the oscilloscope when taking the measurements at 90 W upon which the phase determinations shown in Figure 12-II are based.

Figure 13-II is a composite plot of the amplitude data obtained at 90 W and 459 W. These data were not affected by the noise present at high frequencies in the 90 watt run, because all amplitude data were obtained from the recorder.

In the frequency range of measurement, the transfer function is shown to be essentially the same for these two different power levels. These results when compared with Figures 1 and 2 of Ref. 17 are seen to be in reasonable but not exact agreement. In addition to possible experimental error, the discrepancies might be attributed to the power feedback loops, especially the radiolytic gas feedback loop which has not been completely described analytically. In the theoretical development, the time constant chosen for the gas loop is 1/100 sec. Were this time constant longer, the effect of bubble formation would be more significant in the frequency range of interest, and the theoretical result would be more nearly in agreement with this experiment. Ref. 17 points out that recent experimental results indicate

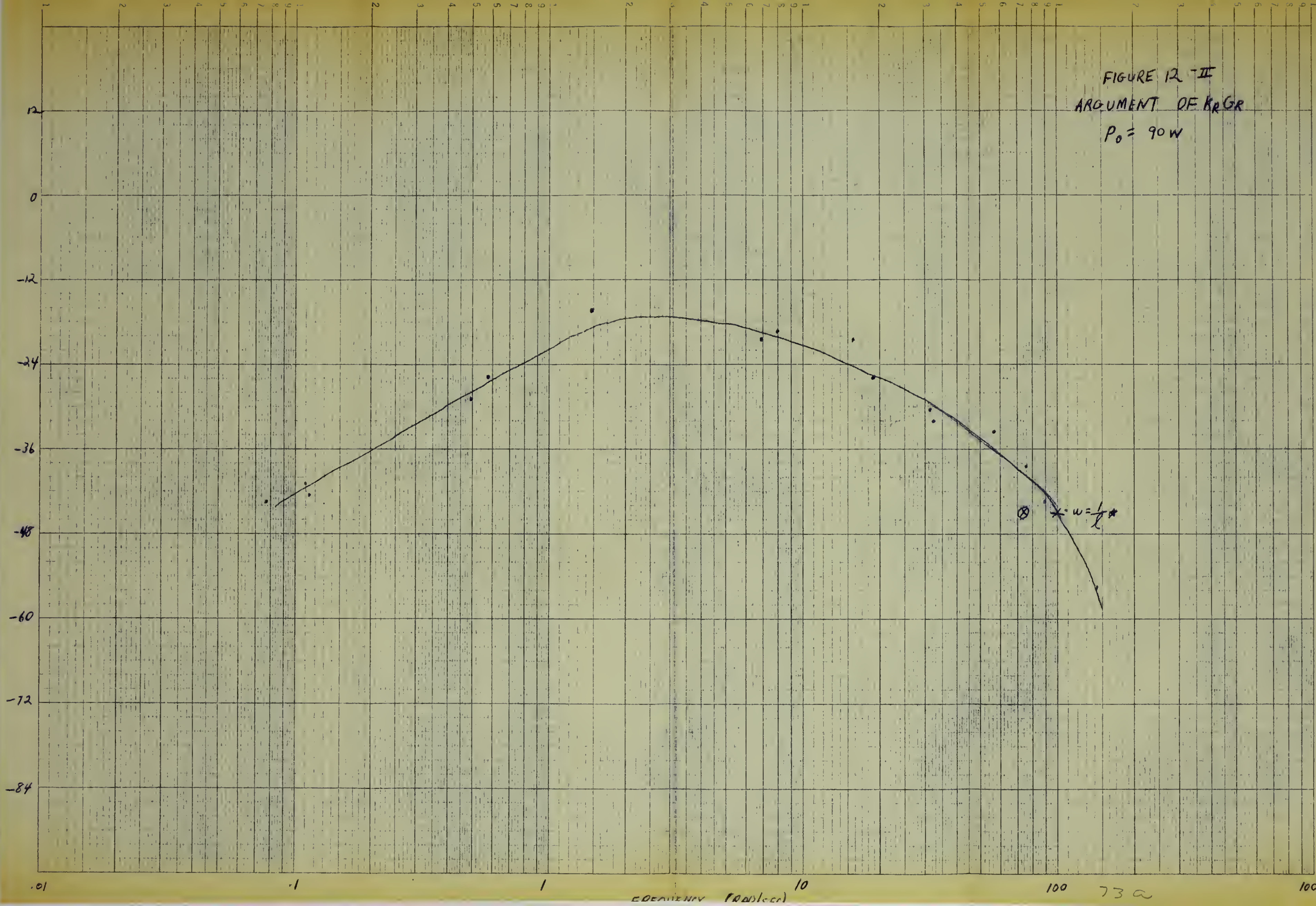


FIGURE 12-II
ARGUMENT OF $K_R G_R$
$P_0 = 90W$
12
0
-12
-24
-36
-48
-60
-72
-84
$w = \frac{1}{\ell^*}$
.01
.1
1
10
100
1000
FREQUENCY (RAD/SEC)

73a

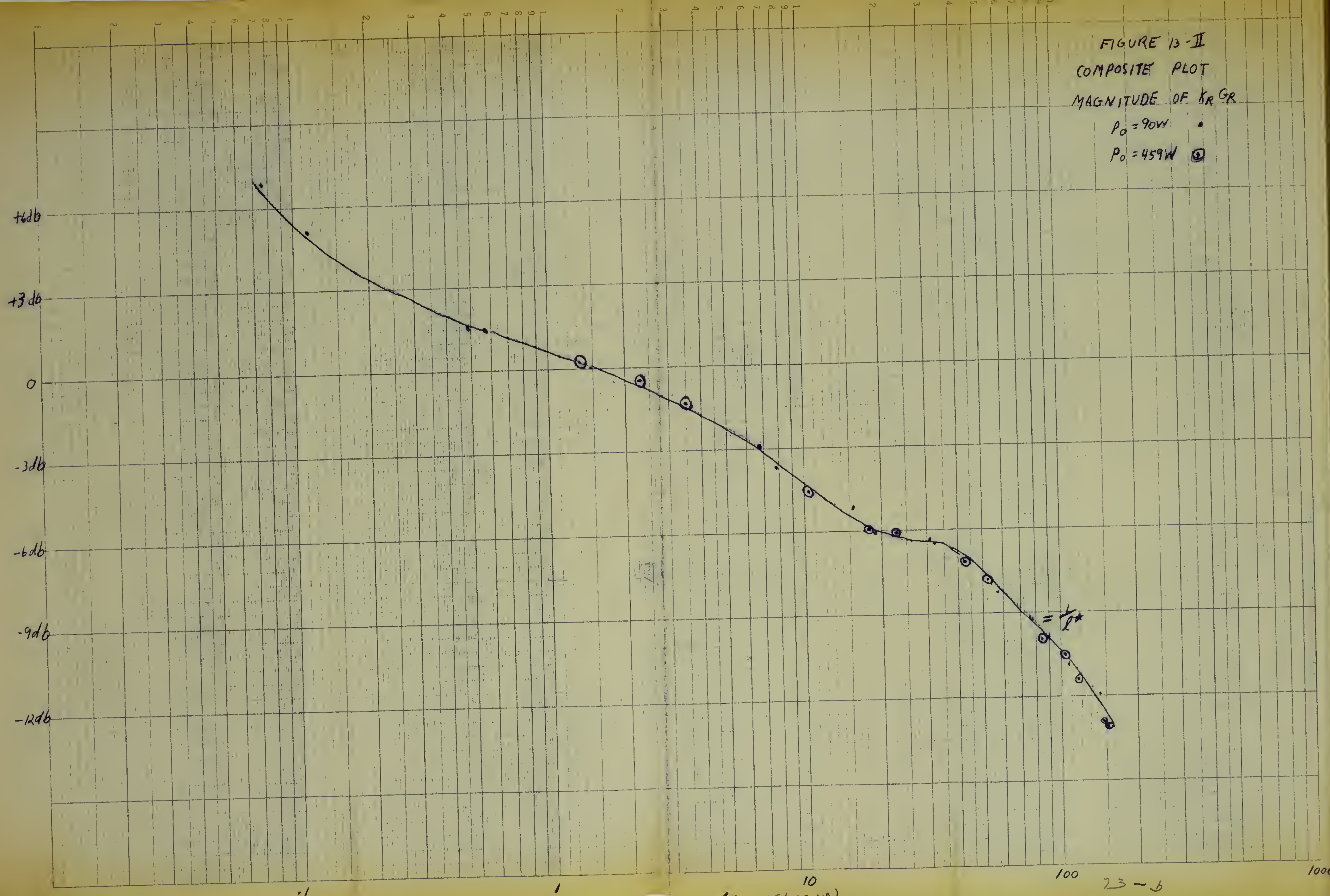


FIGURE 13-II
COMPOSITE PLOT
MAGNITUDE OF $K_R G_R$
$P_o = 90W$
$P_o = 459W$
+6db
+3db
0
-3db
-6db
-9db
-12db
.1
1
10
100
1000

that the analytical transfer function should take into account a dissolved gas stage and an average bubble formation time.

In evaluating the results, one also needs to consider that in the experiment there were deviations from the standard conditions prescribed in the theoretical development. The gas in the sphere was at a pressure less than atmospheric and the characteristics of the cooling system which affect the heat-transfer-feedback loop are not precisely known.

APPENDIX III

MODIFICATIONS AND ADDITIONAL EXPERIMENTS

A. Proposed Changes to the Original Design.

1. The minimum period which will be programmed automatically will be ten seconds. It is compatible with control loop response to program 0.35 volts $\approx$ ten second period.

Assuming 170V power supply, dropping resistor is

$$\frac{170}{0.3} \times 500\Omega = 280\ K \pm 1\%$$

Brown recorder used in the period control loop should be equipped with a 1KΩ retransmitting slidewire instead of a 50KΩ retransmitting potentiometer. Dropping resistor in series with this 1K slidewire is to be 280K $\pm$ 1%. Period run-up potentiometer is to be changed to 1KΩ 1 watt. Period demand potentiometer is to be 500Ω, ten turn Helipot.

2. Versatrol Control Units shown in Table III should be installed to replace the temporary load relay assembly shown in Figure 20. The use of individual load relay power supplies will increase reliability.

3. With the exception of the LE 1366-1C power supplies, entire control chassis is to be enclosed in an aluminum shield to eliminate stray pickup.

4. All leads carrying dc control signals are to be shielded and isolated from other leads in the control chassis insofar as possible. All relay <u>coil</u> leads, external to

versatrol control units, are to be shielded. It is expected that improved shielding will allow removal of the noise filter shown in Figure 18.

5. Log P demand potentiometer is to be changed to 50K.

6. Diode bias resistors in the Log P Comparator are to be changed from 10KΩ to 5KΩ.

7. Initial Rod Drive Potentiometer is to be reduced from 1KΩ to 500Ω ten-turn Helipot.

8. The fixed gain bias curcuit shown in Figure III-1 is to be installed in stage two of the servo amplifier instead of the temporary modification to stage two presently installed. Resistors indicated by symbol number are parts of the unmodified servo amplifier.

Several of the changes proposed herein are merely removal of temporary modifications made necessary in the original model by the short time available for experimentation.

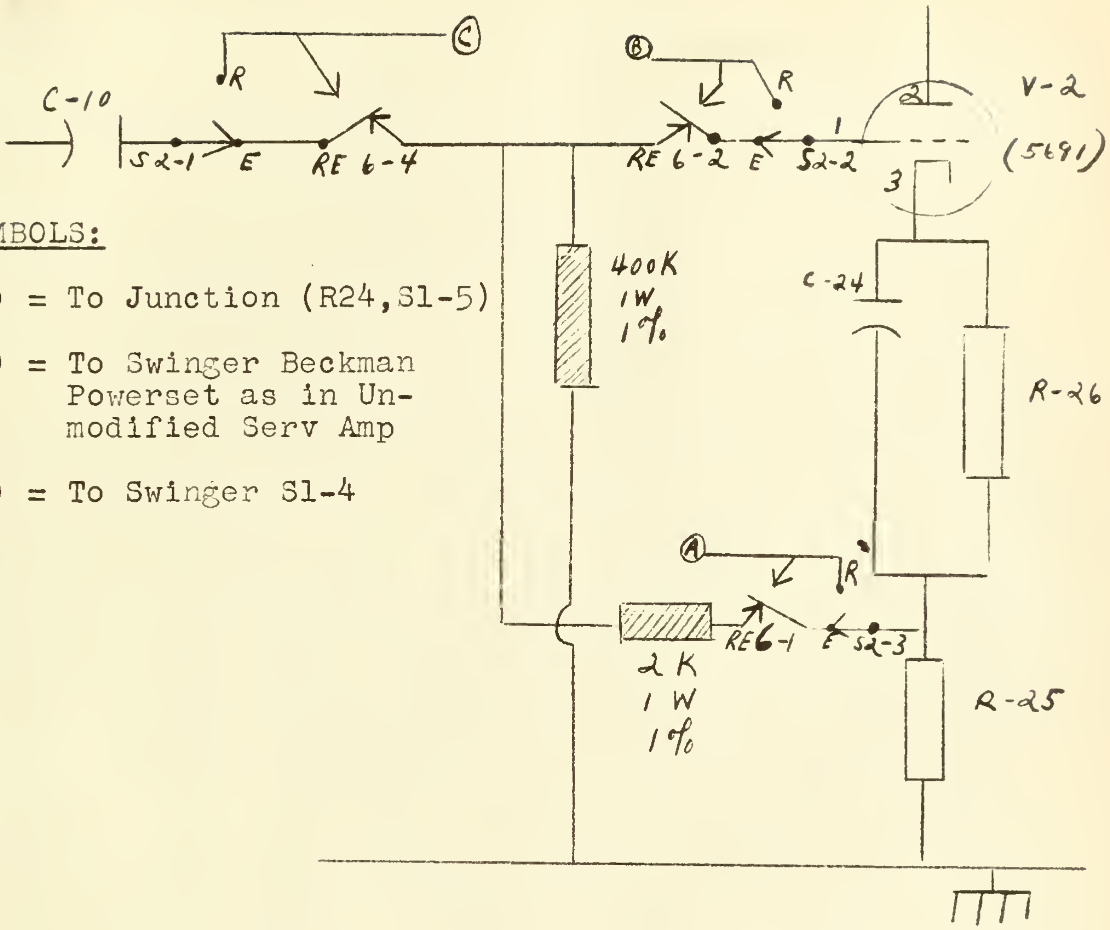
B. Proposed Additional Experiments.

1. Repeated startups from source level, observing the effect of varying Initial Rod Rate Drive.

2. Recalibration of all demand Helipots and meter limit points.

3. A more extensive evaluation of Per - Log P startups.

4. A measurement of the reactor transfer function by the step method at various power levels to obtain data in the frequency range 0.001 to 0.1 radians per second where sinusoidal



SYMBOLS:

(A) = To Junction (R24,S1-5)

(B) = To Swinger Beckman Powerset as in Unmodified Serv Amp

(C) = To Swinger S1-4

Notes:

1. Relay contacts are in Auto-Controller Chassis.

2. Resistors shown shaded may be mounted in Auto-Controller Chassis. Except for RE 6 and S2, all other components were in unmodified serv amp (Ref. UCRL TL 6994E).

3. Temporary modification to servo amp shown in Figure 18 is to be removed prior to accomplishment of this modification.

FIGURE 1 - APPENDIX III

techniques are not effective.

5. A measurement of the reactor transfer function at steady state by correlation techniques to compare with the results already obtained.

C. Other Possible Modifications.

1. Set Back Circuit:

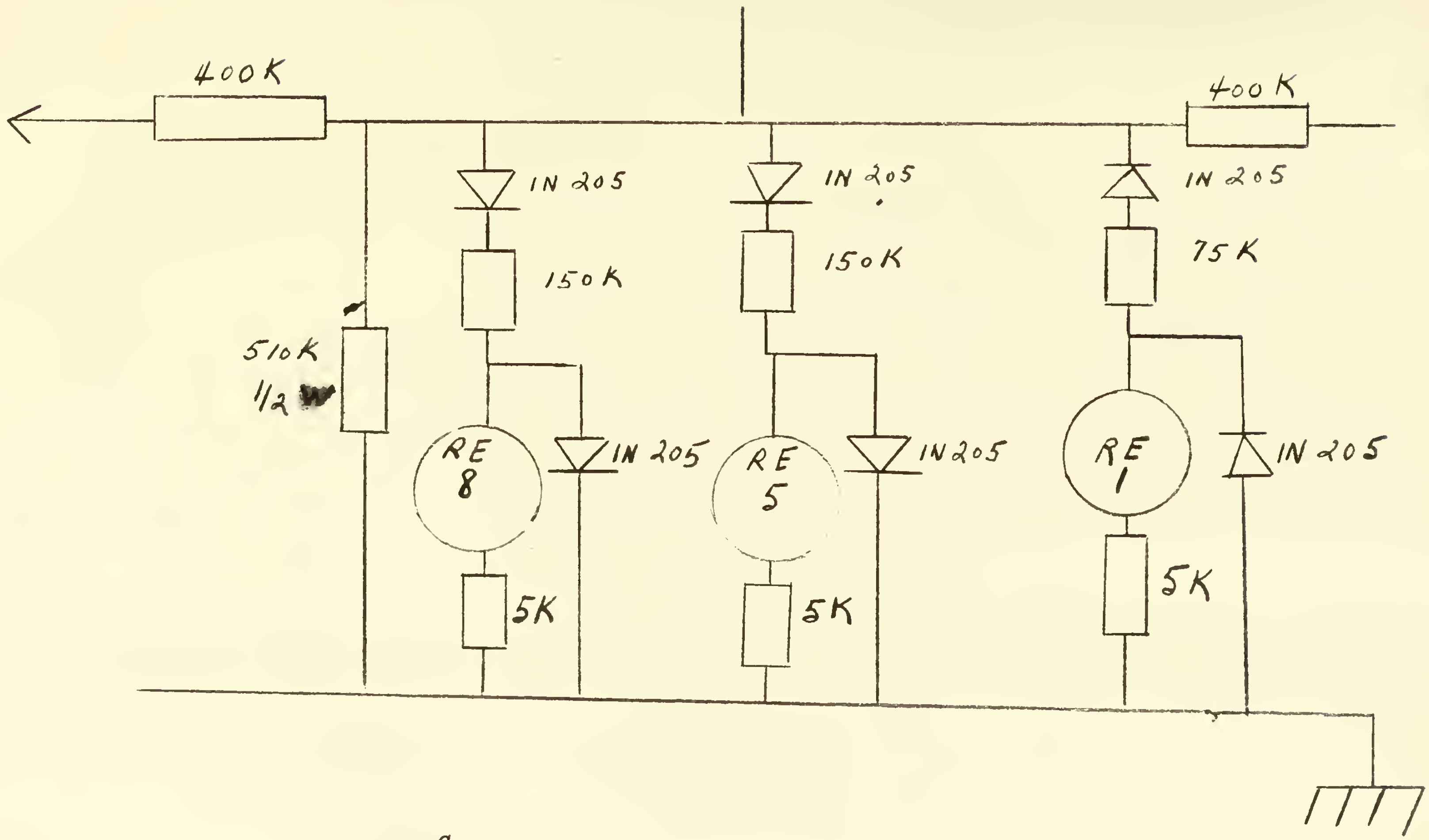
A minor modification to the Log P comparator would allow incorporation of a Setback Circuit. Such a circuit would automatically place the reactor on Log P control and insert the fine rod so as to reduce power level to a level below that demanded by Lin P control. RE 5 must be replaced by a high limit contact Symplytrol. The revised comparator circuit is shown in Figure 2 - III.

2. Dual Mode Control:

By inserting a sensitive relay in the RE 1 coil arm of the Log P comparator, it is possible to allow Per Control whenever the power level goes below the demanded power level by a prescribed amount. This modification is shown in Figure 3 - III. It is not used to remove Log P control because of safety considerations.

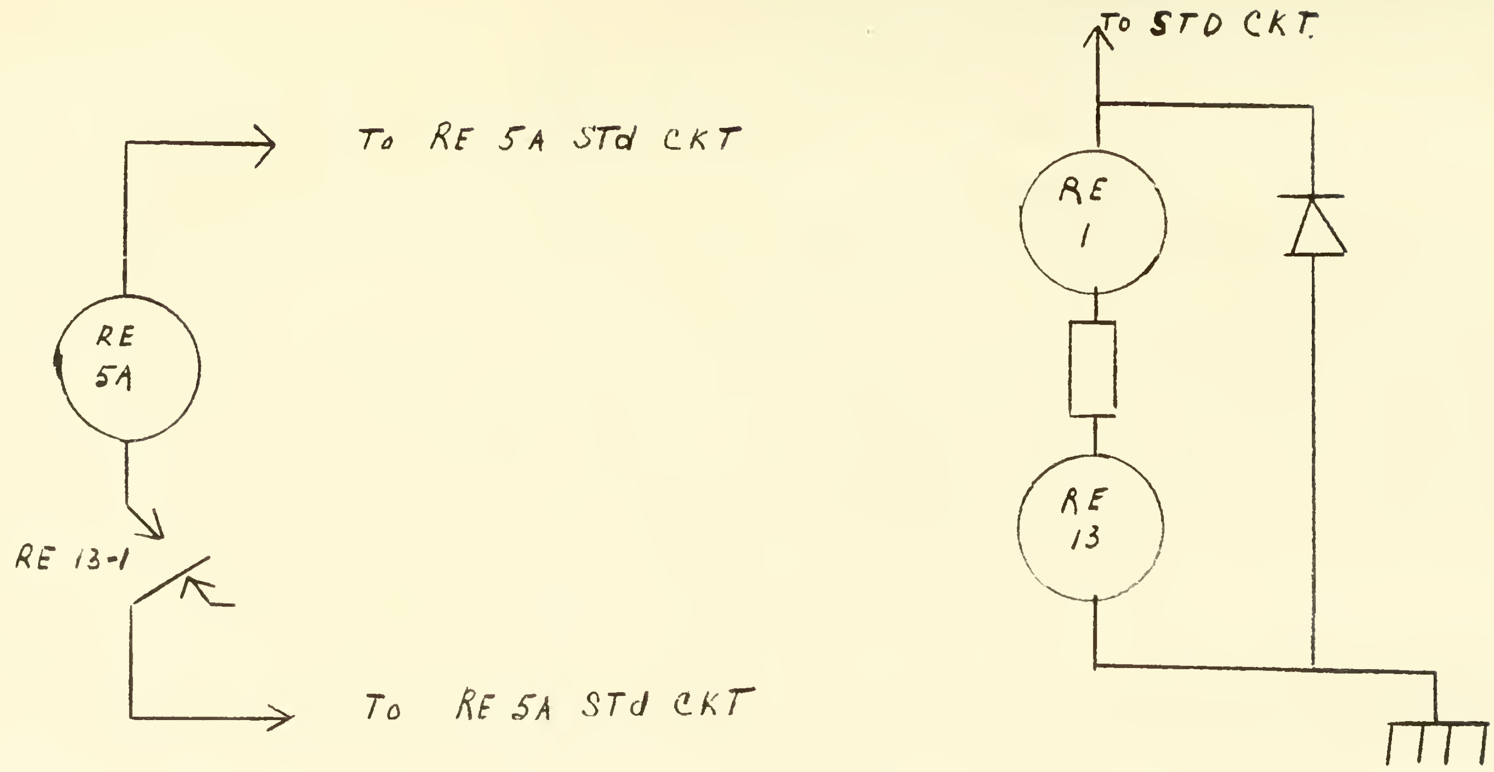
3. Sequential Interlock Circuit:

It is possible to eliminate the need to reset Symplytrol Relays for restarts and provide an added safety feature thereby. This modification is shown in Figure 4 - III.



SETBACK MODIFICATION

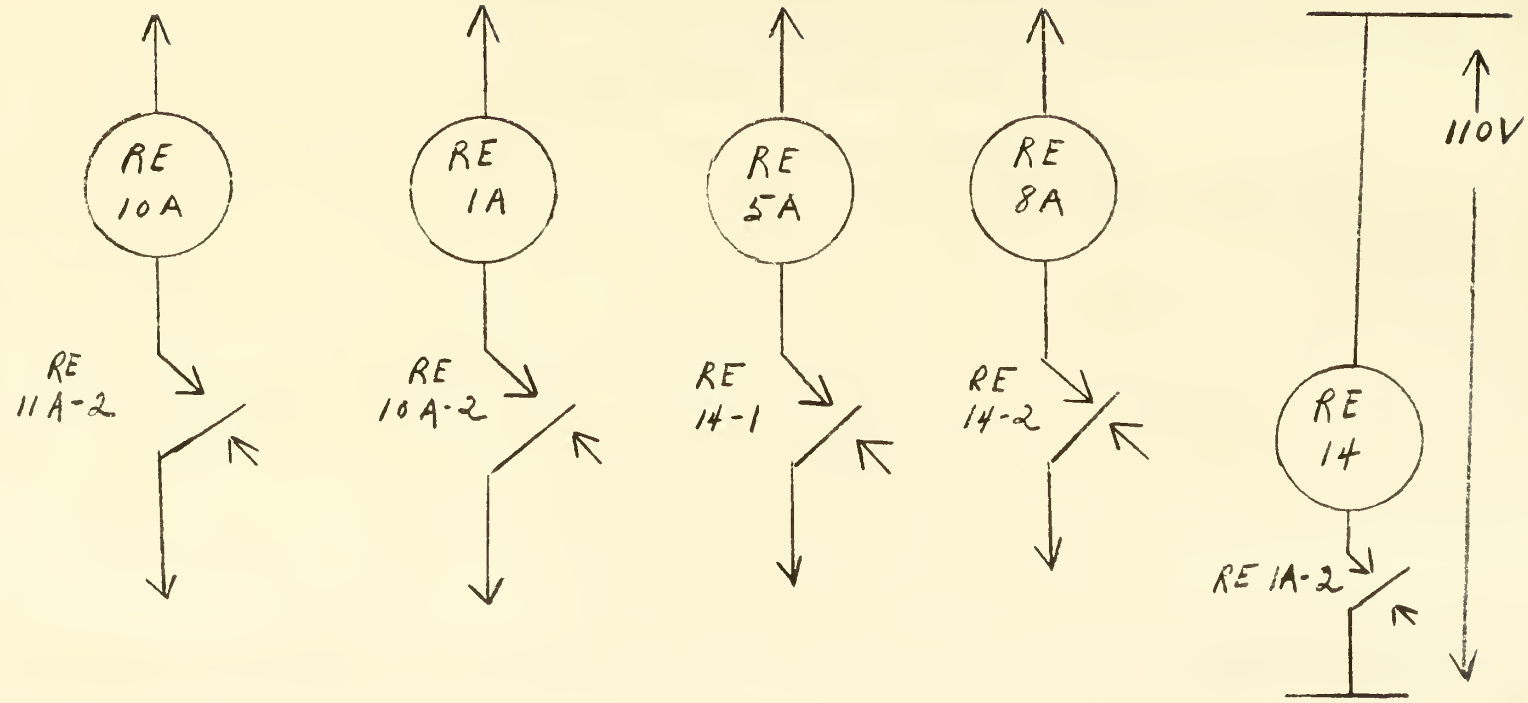
FIGURE 2 — APPENDIX III



(a) (b)

DUAL Mode ModiFiCATioN

FIGURE 3 – APPENDIX III



1. REQUIRES THAT SYMPLYTROL LOAD RELAYS BE DPDT such AS CLARE SK-5028 60V 12.5MA.

2 RESET ON RE 10 IS LEFT AS MANUAL FOR SAFETY REASONS.

SEQUENTIAL INTERLOCK MODIFICATIONS

FIGURE 4 - APPENDIX III

4. Automatic Withdrawal of Safety and Coarse Control Rod:

This modification is a minor one. Since the safety rods are withdrawn sequentially to the full out position, it is only necessary to parallel the manual switch connections with two sequential relays. The coarse rod may be withdrawn a perscribed amount by either a time delay relay or the use of a potentiometer attached to the synchro coarse rod position indicator and a Symplytrol-Relay-actuated stop relay with a manual override switch.